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LIQUEFACTION POTENTIAL OF DAMS AND FOUNDATIONS. REPORT 2. LABOR--ETC(U)
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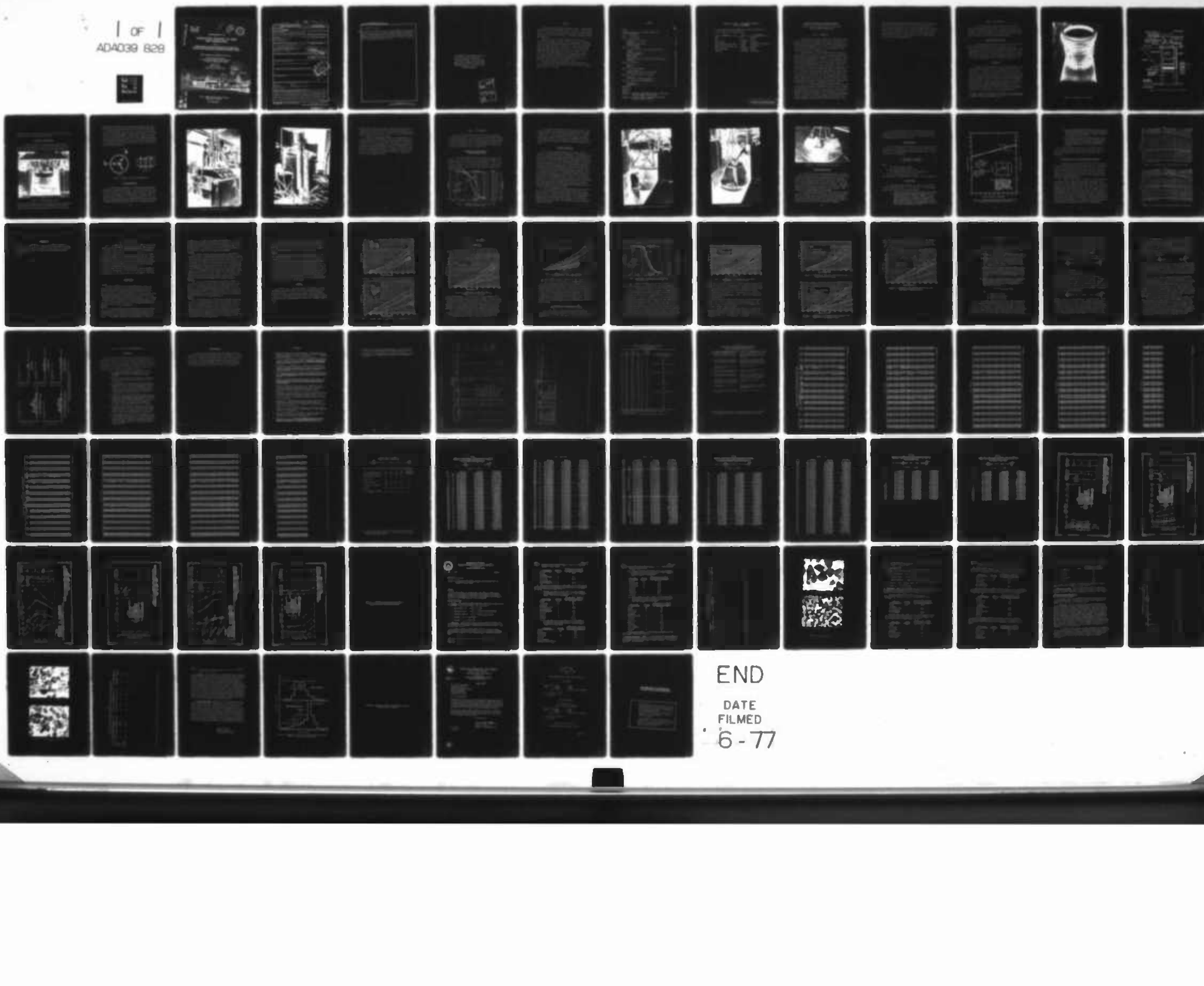

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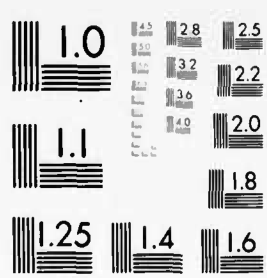

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RESEARCH REPORT S-76-2

LIQUEFACTION POTENTIAL OF DAMS AND FOUNDATIONS

Report 2

LABORATORY STANDARD PENETRATION TESTS ON PLATTE RIVER SAND AND STANDARD CONCRETE SAND

by

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February 1977
Report 2 of a Series

Approved For Public Release; Distribution Unlimited

Prepared for Office, Chief of Engineers, U. S. Army
Washington, D. C. 20314

Under CWIS 31145

(14) WES-RR-S-76-2

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER (9) Research Report ~~S-76-2~~	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) (6) LIQUEFACTION POTENTIAL OF DAMS AND FOUNDATIONS; Report 2, LABORATORY STANDARD PENETRATION TESTS ON PLATTE RIVER SAND AND STANDARD CONCRETE SAND.		5. TYPE OF REPORT & PERIOD COVERED Report 2 of a Series
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) (10) Wayne A. Bieganousky William F. Marcuson, III		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS U. S. Army Engineer Waterways Experiment Station Soils and Pavements Laboratory P. O. Box 631, Vicksburg, Miss. 39180		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS CWIS 31145
11. CONTROLLING OFFICE NAME AND ADDRESS Office, Chief of Engineers, U. S. Army Washington, D. C. 20314		12. REPORT DATE (11) February 1977
		13. NUMBER OF PAGES 87 (12) 94p.
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Dams	Sands
Foundations	Soil tests
Liquefaction (Soils)	Standard penetration tests
Relative density	

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The Standard Penetration Test (SPT) is critically examined with respect to its ability to estimate relative density in situ. Six test specimens, 4 ft in diameter by 6 ft high, were constructed using Platte River sand and Standard Concrete sand. SPT's were performed, using field drilling equipment, on specimens under three overburden pressures and constructed to three relative densities. The results are presented as a family of curves correlating relative density with SPT N-values at the three overburden pressures. This research is → cont
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20. ABSTRACT (Continued).

an extension of a previous test series on Reid Bedford Model sand and Ottawa sand. The results from tests of the four sands are compared, and a statistical analysis is presented which produced an empirical equation relating relative density to overburden pressure, SPT N-value, and coefficient of uniformity. Comparisons are also made between this work and that of Gibbs and Holtz at the Bureau of Reclamation and Bazaraa at the University of Illinois. Conclusions are presented based on both series of tests.

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PREFACE

The study reported herein was performed at the U. S. Army Engineer Waterways Experiment Station (WES) as part of the Office, Chief of Engineers, U. S. Army (OCE), Civil Works Research effort. The investigation was authorized by OCE under CWIS 31145, "Liquefaction Potential of Dams and Foundations."

WES engineers who were actively engaged in this study were Dr. William F. Marcuson III and Mr. Wayne A. Bieganousky. The laboratory tests were performed by Engineering Technicians Melvin M. Carlson, Donald H. Douglas, and Edwin S. Stewart, Jr. The work was conducted under the general supervision of Dr. Francis G. McLean, Chief, Earthquake Engineering and Vibrations Division, and Mr. James P. Sale, Chief, Soils and Pavements Laboratory. This report was prepared by Mr. Bieganousky and Dr. Marcuson and reviewed by Professor J. H. Schmertmann, University of Florida, Gainesville, Fla. Mr. R. R. W. Beene was technical monitor of this study for OCE.

During the study and the preparation of this report, COL G. H. Hilt, CE, and COL John L. Cannon, CE, were Directors of WES. Technical Director was Mr. F. R. Brown.

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CONVERSION FACTORS, U. S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

U. S. customary units of measurement used in this report can be converted to metric (SI) units as follows:

Multiply	By	To Obtain
inches	25.4	millimetres
feet	0.3048	metres
pounds (mass)	0.4535924	kilograms
pounds (mass) per cubic foot	16.01846	kilograms per cubic metre
pounds (force) per square inch	6.894757	kilopascals
degrees (angular)	0.01745329	radians
cubic feet	0.02831685	cubic metres

LIQUEFACTION POTENTIAL OF DAMS AND FOUNDATIONS

LABORATORY STANDARD PENETRATION TESTS ON PLATTE RIVER SAND AND STANDARD CONCRETE SAND

PART I: INTRODUCTION

1. Following the San Fernando earthquake on 9 February 1971, the Corps of Engineers (CE) initiated a research study concerned with the liquefaction of dams and foundations. One segment of the planned research involved an assessment of CE ability to reliably determine relative density, since relative density is a controlling factor in the liquefaction potential of cohesionless soils.

2. Relative density is often determined indirectly through correlations with field test results. One such correlation enjoying widespread usage relates Standard Penetration Test (SPT) N-values,[1] relative density, and overburden pressure. A family of curves expressing this relationship was published in 1957 by Gibbs and Holtz[2] that was based on a series of full-scale laboratory tests. Many engineers employ the Gibbs and Holtz correlation in routine site analyses, and some have used the correlation to predict the liquefaction potential of cohesionless soils. Estimates of relative density obtained from the results of SPT's have been a target of criticism,[3] since some practicing engineers see little value in either the SPT or the relative density concept. Nevertheless, many continue to use the SPT, and lately the trend has been to relate liquefaction potential directly to SPT N-values, thereby circumventing the errors[4] inherent in determining relative density.[5,6]

3. The U. S. Army Engineer Waterways Experiment Station (WES) has recently conducted a series of laboratory tests in an effort to examine the reproducibility of SPT results and the accuracy of relative density predictions based on SPT N-values. Several sand types were tested to determine if grain size distribution or grain shape influenced the penetration resistance. The tests were performed in a special soil container at varying relative densities and overburden pressures. Reid

Bedford Model sand and Ottawa sand were tested during the first phase of the SPT study, and the results were published in an earlier report.[7] This is the second and final report on the SPT study and includes results obtained from testing Platte River and Standard Concrete sands. The results from tests of each sand were compared and statistically analyzed. These comparisons as well as comparisons with earlier correlations by other researchers are presented herein.

PART II: TEST EQUIPMENT

4. Since the components of the test facility are described in detail in the earlier SPT report,[7] only a brief description will be given here. The major components are a 4-ft-diam* by 6-ft-high stacked-ring soil container, the foundation, a loading system for applying overburden pressures, and the drilling and sampling equipment.

Stacked-Ring Soil Container

5. The stacked-ring soil container (Figure 1) consists of alternating layers of steel rings with 1-in.-square cross section and 3/16-in.-thick rubber spacers in a tongue-and-groove configuration. The stacked-ring soil container serves to minimize the reduction in vertical stress due to friction that is common in solid wall containers. Observations during testing indicated that approximately 99 percent of the applied load was transmitted to the soil specimen at a depth of 6 ft.[8]

Foundation

6. Figure 2 is a cross-sectional view of the test apparatus. Two 4-ft-high concrete pedestals react the overburden loading system (discussed below). The top of the foundation monolith is at floor level. For these tests, specimens were built over a 4-ft-diam well which extends 6-1/2 ft through the concrete foundation to a sand blanket overlying the natural substratum. The well was backfilled with highly compacted Reid Bedford Model sand. Layers of graded filter material were provided in the dense backfill to enable specimen submergence from the bottom up. A perforated water hose was threaded through the cable way to the rock filter, and an auxiliary water hose was used to maintain approximately equal water levels inside and outside the specimen during the

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* A table of factors for converting U. S. customary units of measurement to metric (SI) units is presented on page 5.

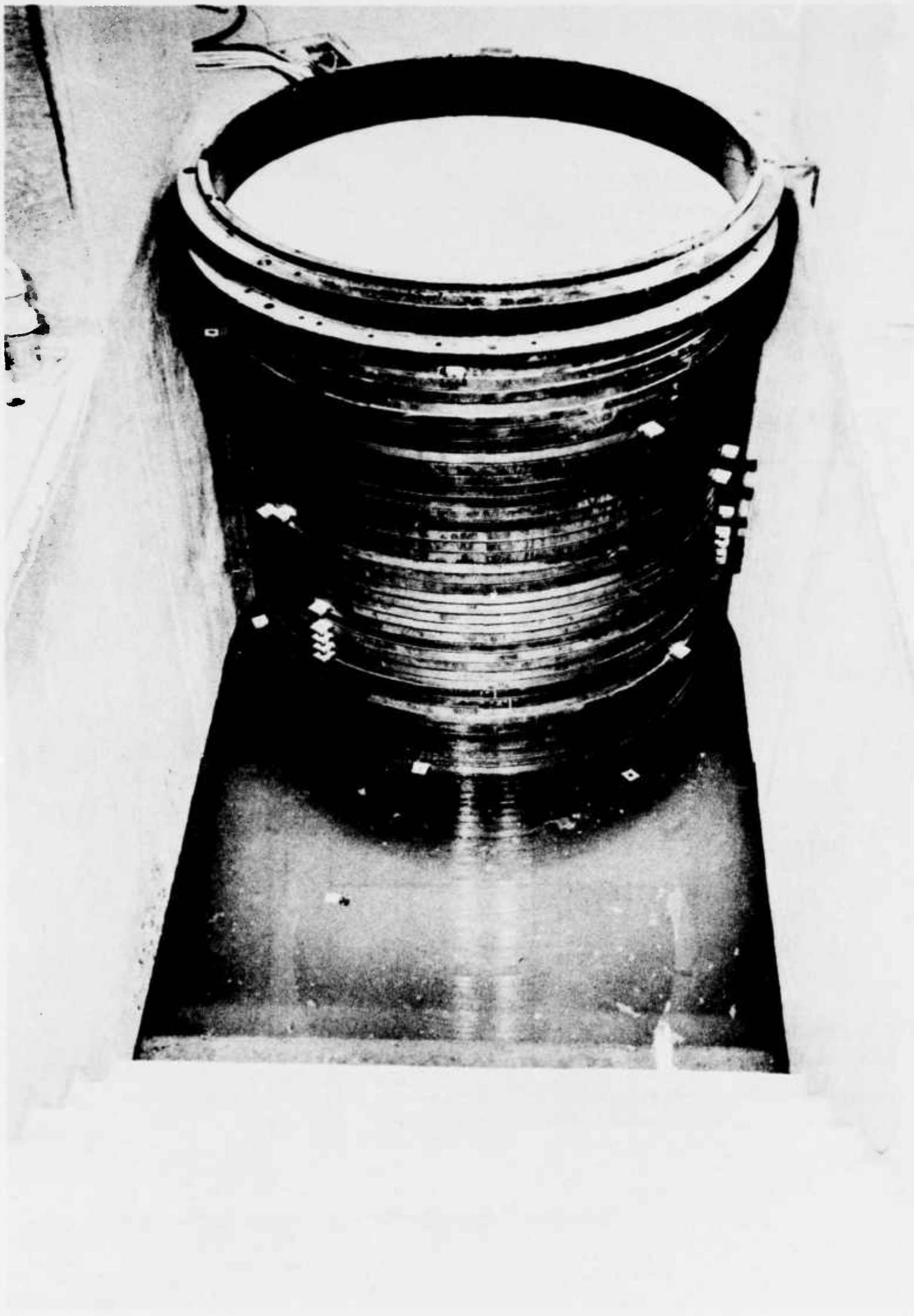

Figure 1. Stacked-ring soil container

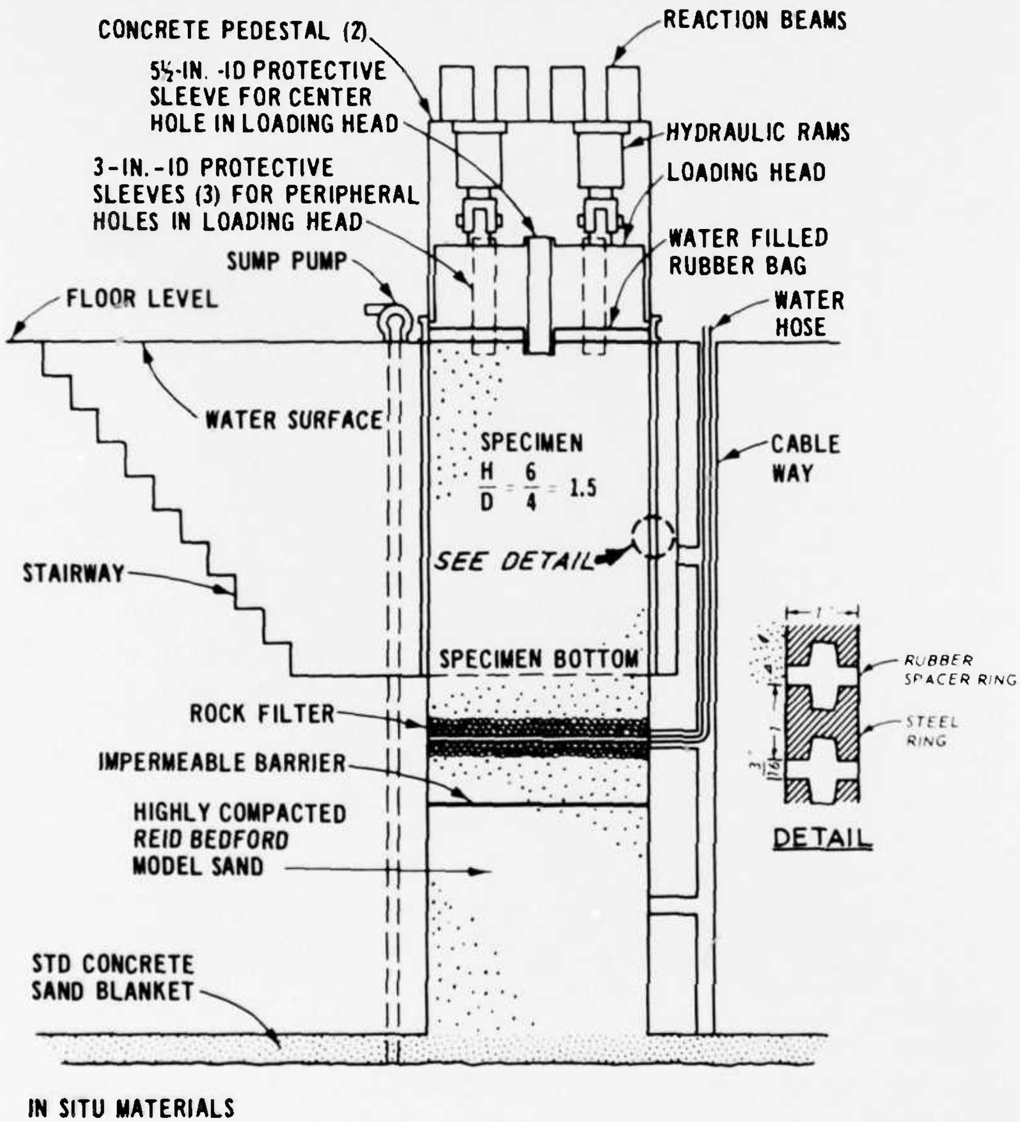

Figure 2. Cross-sectional view of test apparatus

submergence phase. The impermeable barrier prevented water in the specimen from draining into the foundation materials.

Overburden Loading System

7. Overburden pressure, simulating testing at desired depths beneath the ground surface, was applied with an overburden loader (Figure 3). The loader consists of a ram and reaction beam assembly, a

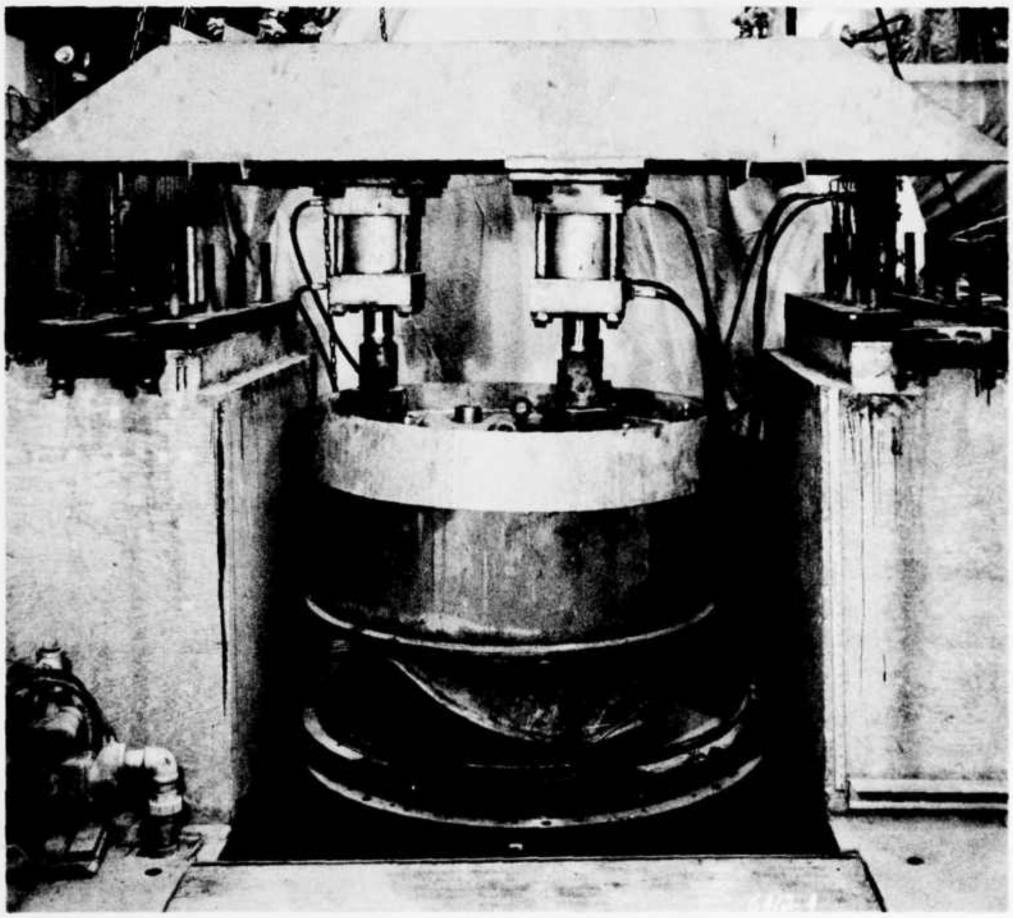

Figure 3. Overburden loader system

cylindrical steel loading head, and a fiberglass-reinforced rubber water bag. Vertical load was applied to the loading head by three hydraulic rams, while the reaction beam assembly, anchored to the two concrete pedestals shown, countered the vertical force developed by the rams. The water bag between the loading head and the specimen surface served to uniformly distribute the vertical load. The rams were individually driven by three manually operated hydraulic pumps mounted on a portable console containing the hydraulic fluid reservoir. Hydraulic pressure delivered to each ram was monitored with a console-mounted Bourdon gage. The loading head was outfitted with four sleeves which extended through the loading head and water bag and penetrated 2 in. into the surface of the soil specimen (Figure 4).

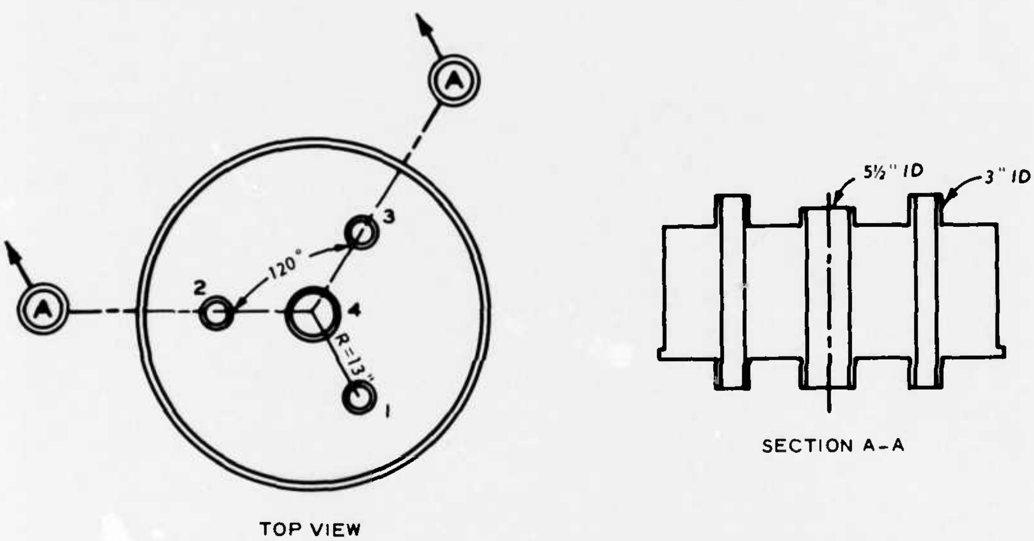

Figure 4. Location of sleeves in loading head

Drilling Equipment

8. The SPT's were performed with a commercially available skid-mounted soil sampling drill (Figure 5). The rig was elevated on a platform, level with the top of the loader support pedestals. N-size drill rods were used throughout the testing program. The maximum length of drill rods did not exceed 11 ft, and the minimum length was 5 ft. The split spoon sampler was driven by a hydraulically operated 140-lb hammer contained in a perforated cylinder (Figure 6). The hammer was lifted

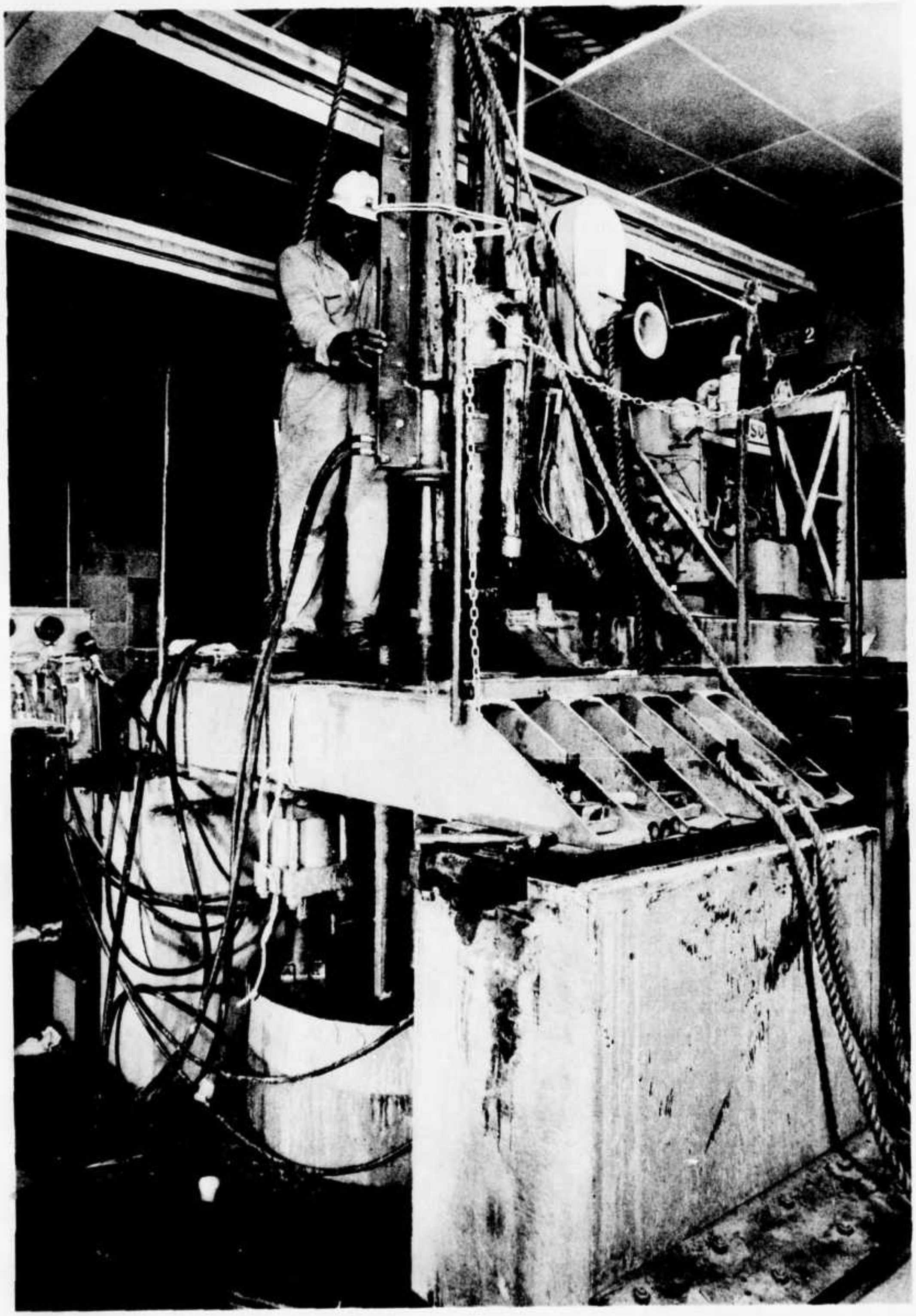

Figure 5. Test facility in operation

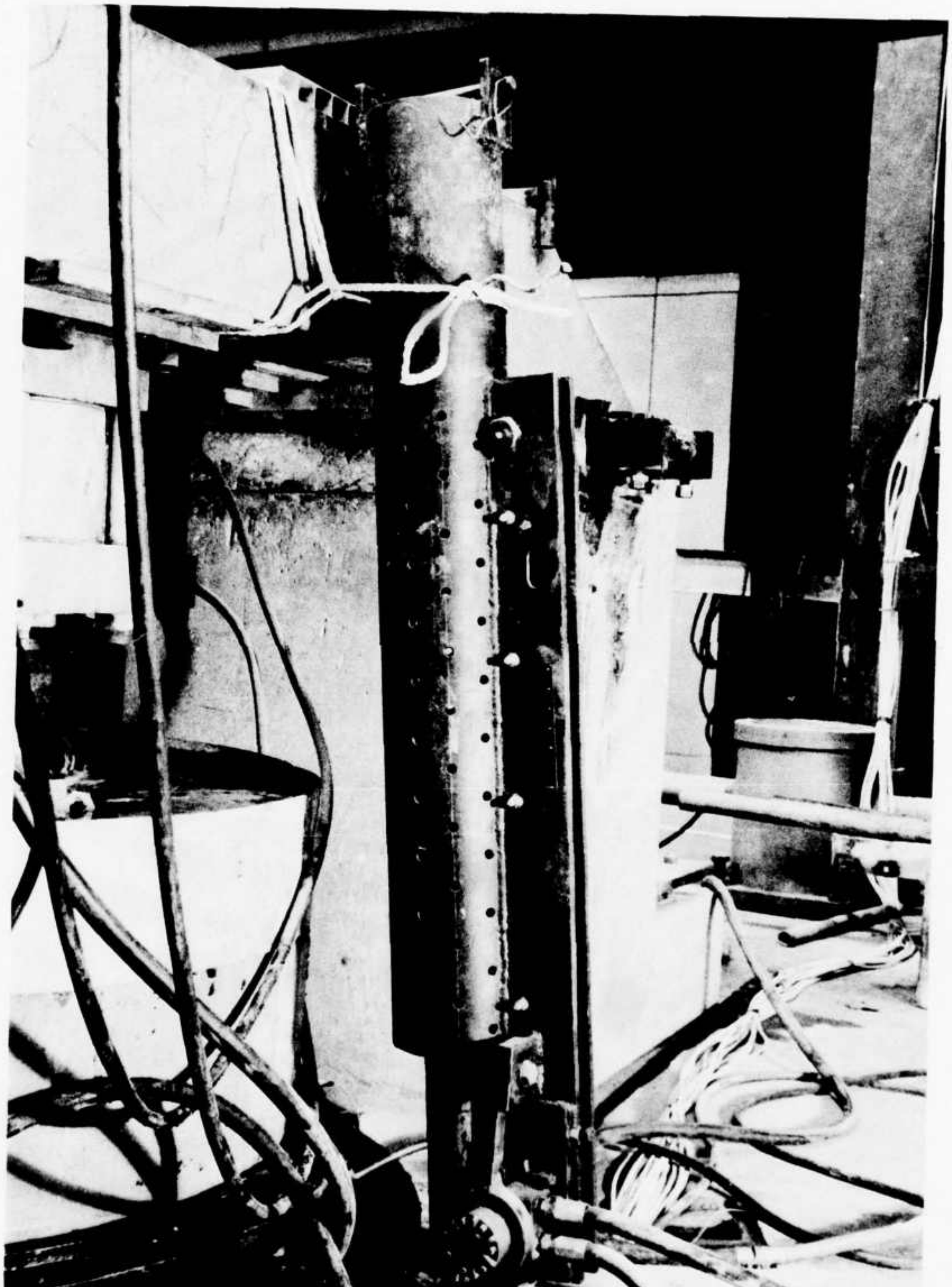

Figure 6. Hydraulically driven 140-lb trip hammer

mechanically to a 30-in. drop height by one of two lugs positioned on a continuous chain that was driven by a hydraulic motor connected to the hydraulic system of the drill rig. The rate of driving was approximately 15 blows per minute for the entire study.

9. The split spoon sampler conformed to the specifications outlined in American Society for Testing and Materials (ASTM) Designation: D 1586-67[1]; however, no liner was used. This condition is similar to that which exists in actual practice. The borehole was advanced using a fishtail bit modified by WES and drilling mud. The WES modification consisted of adding special baffles to a commercial bit, which directs the flow of drilling mud in an upward direction, thus reducing disturbance at the next sampling level.[9]

PART III: TEST PROGRAM

10. The SPT results reported herein are for six 4-ft-diam by 6-ft-high specimens tested at various relative densities under a range of overburden pressures. Table 1 summarizes the entire test program and includes information of a general nature regarding the preparation and testing of the specimens. Tests 1-26 were reported previously,[7] and this report presents the results of Tests 27-32.

Properties of Platte River and Standard Concrete Sands

11. Two poorly graded sands were used during this phase of the program. The first was Platte River sand procured from Denver, Colo., which is similar to the sand used by Gibbs and Holtz.[2] It has a coefficient of uniformity of 5.3, a median grain size of 2.0 mm, and a subrounded grain shape. Figure 7 depicts the grain size distribution of the Platte River sand.

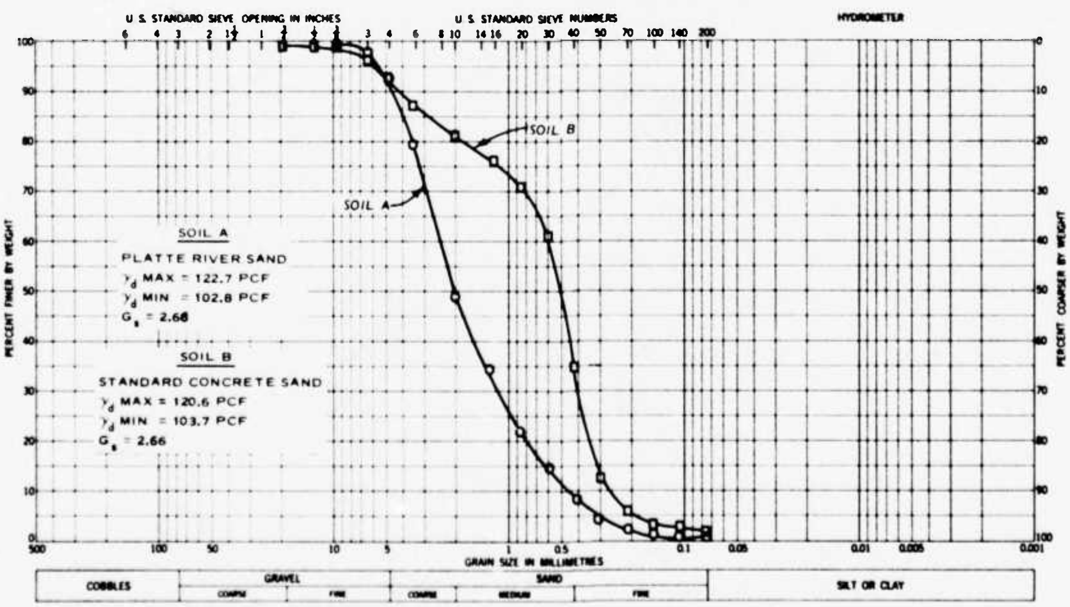

Figure 7. Mechanical analyses of Platte River sand and Standard Concrete sand

12. Standard Concrete sand was the second sand tested. It was procured locally, and it nearly meets CE specifications for Standard Concrete sand. It has a coefficient of uniformity of 2.1, a median grain size of 0.5 mm, and a subrounded to well rounded grain shape. Also plotted in Figure 7 is the grain size distribution of the Standard Concrete sand. Appendix A contains petrographic analyses of both sands.

Specimen Construction

13. The sand was placed by raining it through a single hose attached to a funnel-shaped reservoir (Figure 8). The least dense specimens (i.e., those with the lowest relative density) were made by allowing the sand to free fall through the hose to the specimen surface with the outlet of the hose 1 to 2 in. above the sand surface. The specimens were built incrementally, in 6-in. lifts, with density determinations made for each lift (as discussed below). Dense specimens were made by vibrating each lift for a specified time interval. The vibrator was an a-c powered, 60-Hz, eccentric rotating mass vibrator mounted on one of two platforms (Figures 9 and 10). The vibrator mounted on plywood was used to densify the specimen constructed for Test 28, and the vibrator mounted on the steel platform was used to prepare specimens for Tests 29, 31, and 32. The need for the steel platform arose when it was discovered that the vibrator mounted on plywood could not produce high-density lifts. The three 310-lb cast iron weights shown positioned on the steel platform in Figure 10 were used as ballast.

14. Due to the gradations of the tested sands, it was very difficult to place the materials by the methods used during the previous phase of testing.[7] The wide variation in grain sizes caused segregation of particles to occur, and it was not possible to rain a homogeneous specimen by the previously established techniques. The single-hose rainer provided the best control over segregation but did not completely eliminate the problem.

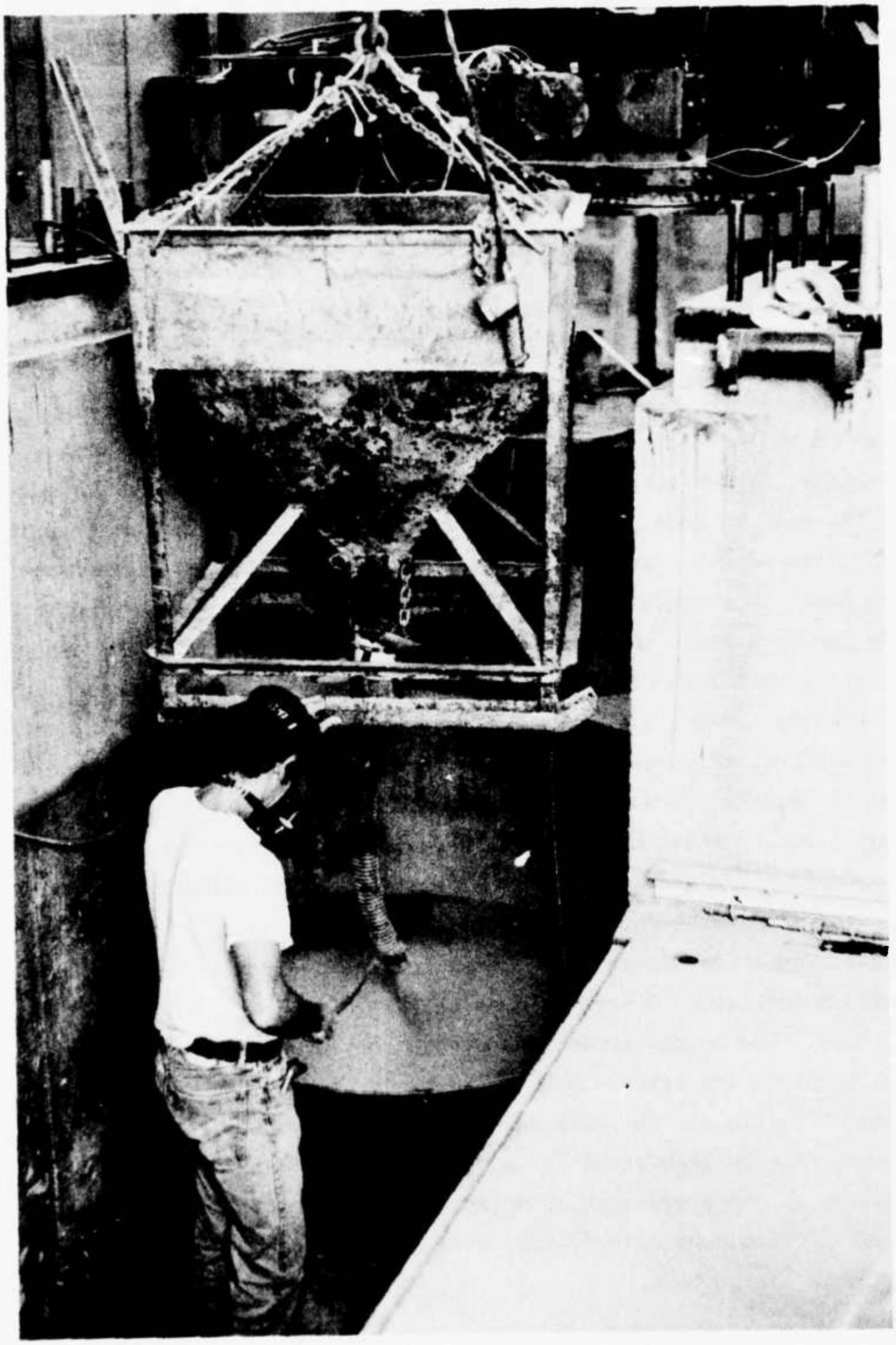

Figure 8. Depositing sand with a single-hose rainer

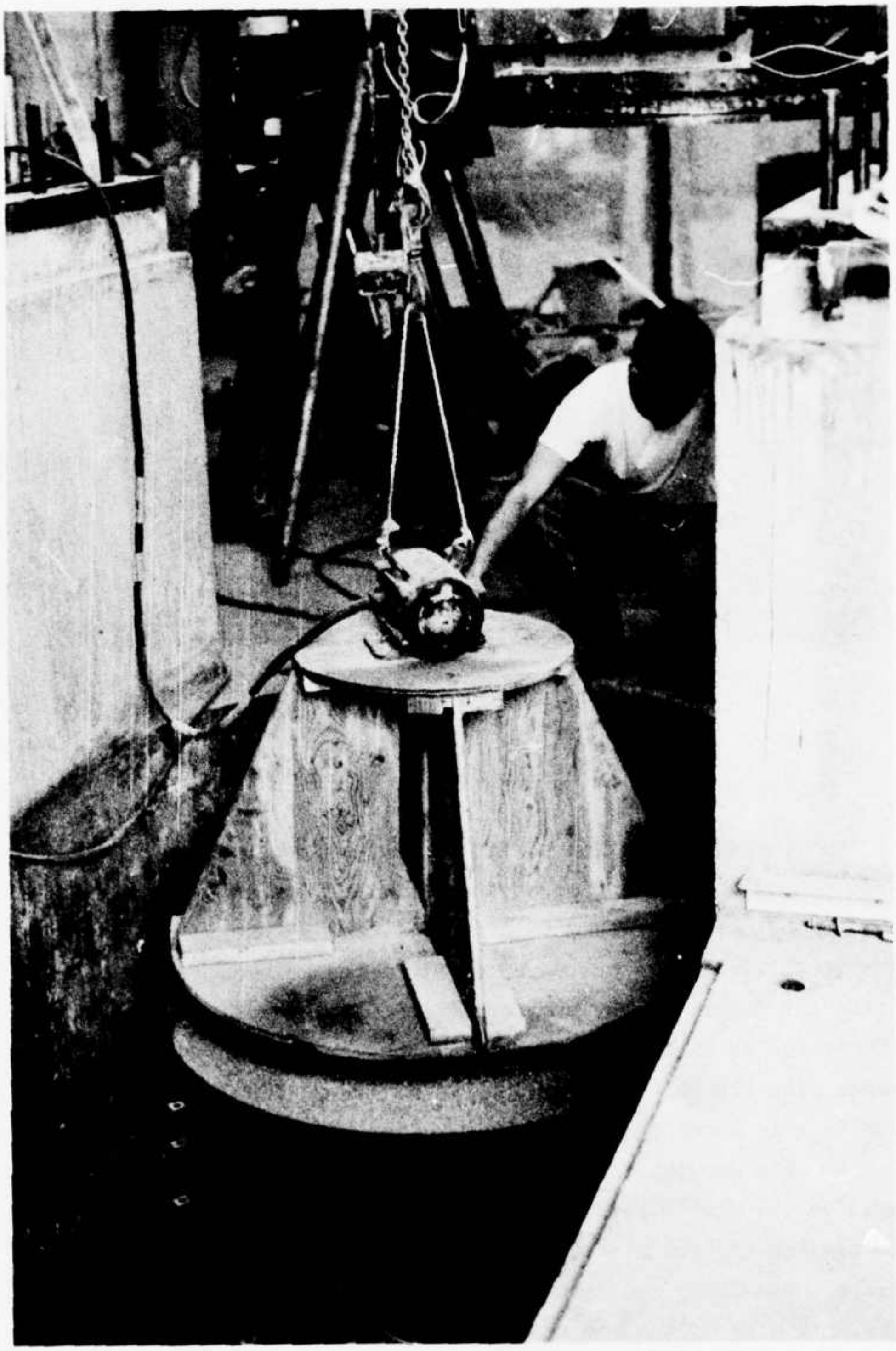

Figure 9. Vibrator with plywood support

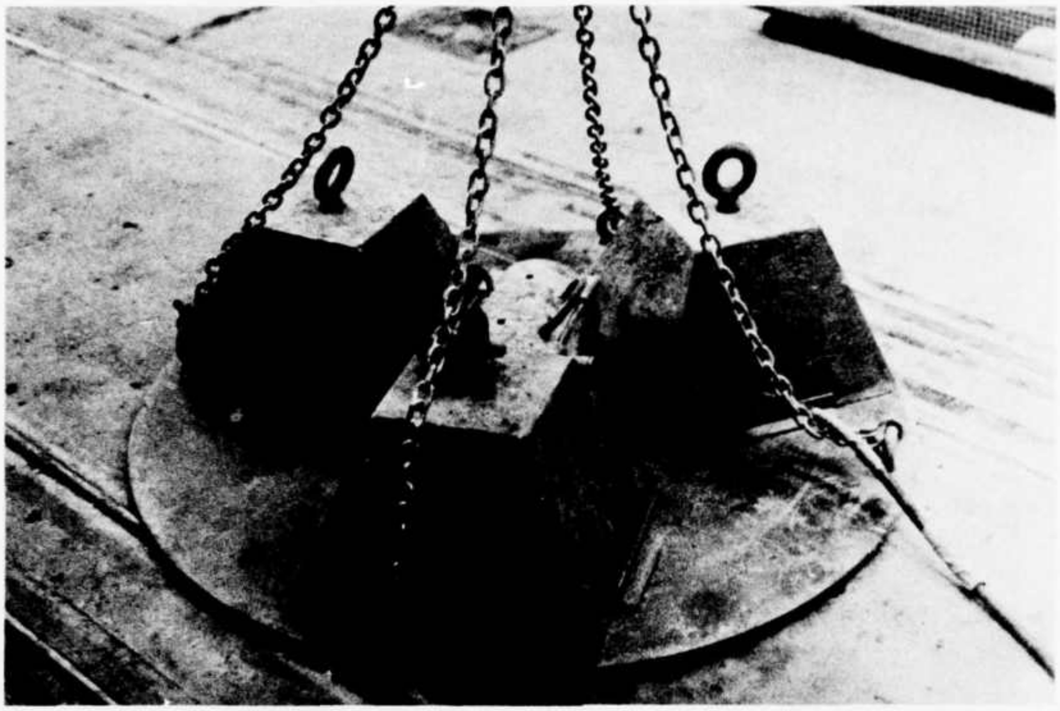

Figure 10. Vibrator mounted on steel plate

Density Determinations

15. The density of each lift was determined based on the weight of sand placed and the volume of the container filled by that lift. The weight of the material was determined by weighing the raining device plus soil and deducting the tare weight of the rainer. The volume of the lift was determined by precise differential leveling. The average density value obtained for all the lifts of a specimen was subsequently compared with the bulk density determined for that specimen. These values were in close agreement for all specimens.

16. The density values reported for a given test are the average values for the middle third of the specimen. This area corresponds to that used for the two middle SPT drives, which were considered most reliable. The first and last drives were considered less reliable due to the proximity of the top and bottom specimen boundaries.

17. In the previous WES tests,[7] a box density device was used to obtain the densities of each lift. However, densities determined with the same box density device were inaccurate for these sands due to the size and gradation of the sand particles.

Relative Density

18. The maximum and minimum dry densities of the respective sands were determined by the procedures contained in Engineer Manual EM 1110-2-1906.[10] Once the maximum and minimum densities were known, the relative density was computed from

$$D_R = \left[\frac{\gamma_{d\ max}(\gamma_d - \gamma_{d\ min})}{\gamma_d(\gamma_{d\ max} - \gamma_{d\ min})}\right]100 \qquad (1)$$

where

D_R = relative density, percent

$\gamma_{d\ max}$ = densest packing of the soil, pcf

γ_d = density of the material in the specimen, pcf

γ_d min = loosest packing of the soil, pcf

This relationship is shown graphically in Figure 11 for the sands tested.

Stage Testing

19. Penetration resistance data were compiled for each specimen at three overburden pressures: 10, 40, and 80 psi. The procedure was termed "stage testing" and proceeded as follows:

a. With a 10-psi overburden pressure applied, an undisturbed sample was taken in the center hole from the 0- to 2-ft depth with a Hvorslev fixed-piston sampler. The next sampling operation was a series of SPT's for the full depth of the specimen, performed in a peripheral hole under the same pressure. Steel rods having the approximate diameter of the vacated holes were used to stem the holes to check sloughing. The stemming operation was conducted after each clean-out operation.

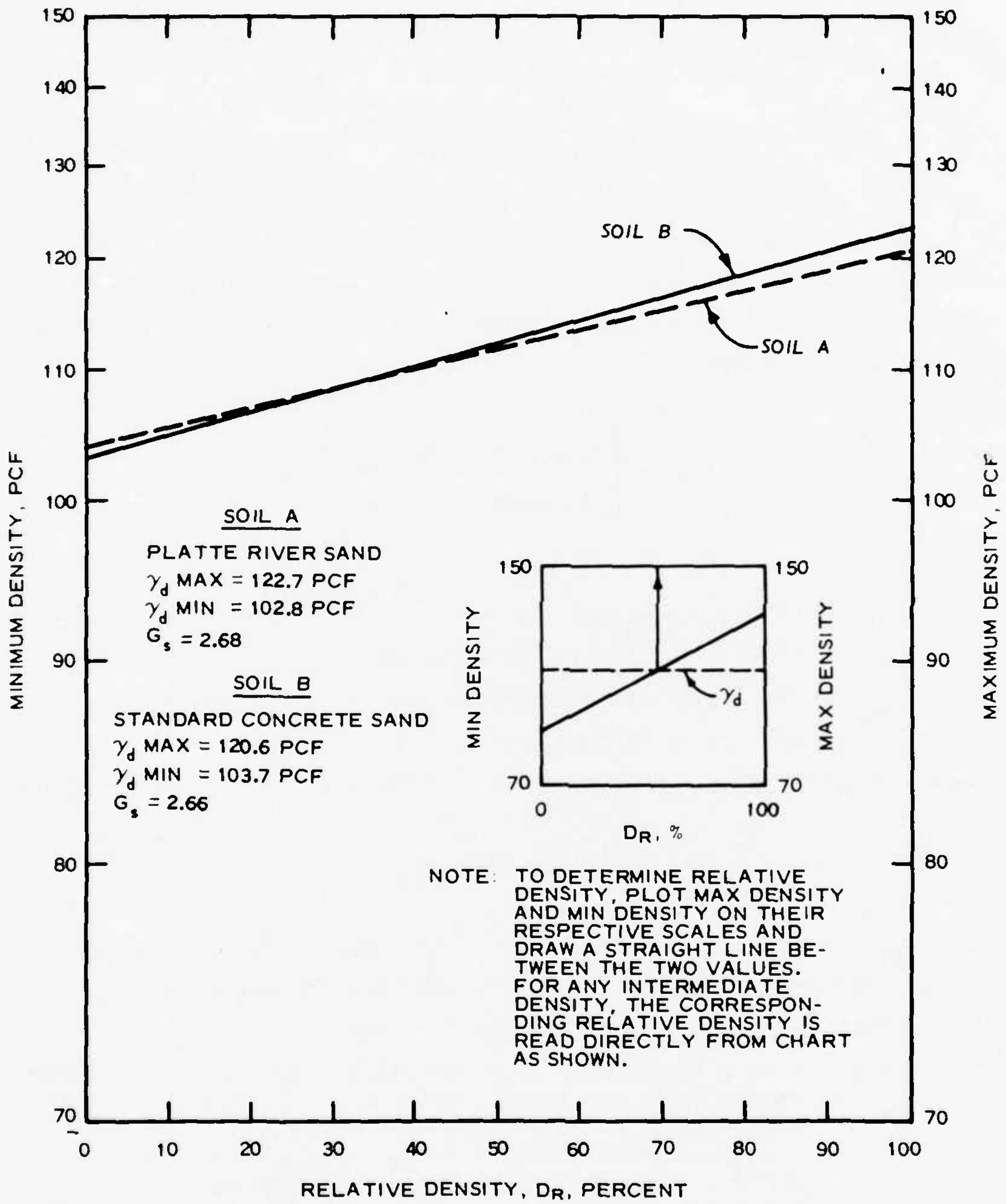

Figure 11. Graphical determination of relative density for Platte River sand and Standard Concrete sand

b. The overburden pressure was increased to 40 psi, and a sample was obtained from the 2- to 4-ft depth in the center hole using a Hvorslev sampler. A series of SPT's was then run in a second peripheral hole for the full depth of the specimen at that pressure.

c. The overburden pressure was increased to 80 psi, and a final drive was made with the Hvorslev sampler at the 4- to 6-ft depth in the center hole. The final series of SPT's was then run at the same testing pressure in the last peripheral hole for the full depth of the specimen.

20. Stage testing was effective in that it provided data at three testing pressures and required only one specimen. Adverse effects on the results due to stage testing are not believed to be significant.

Consolidation Due to Overburden Pressure Application

21. Application of the overburden pressure caused consolidation within the specimen; densification was significant for loosely prepared specimens and minimal for the higher density specimens. The density increase corresponding to a given overburden pressure was calculated from the results of one-dimensional consolidation tests performed on submerged 3-in.-diam specimens at the same testing pressures as those used in the laboratory SPT program.

22. Figures 12 and 13 present the results of the one-dimensional consolidation tests in terms of density versus log pressure on the Platte River sand and Standard Concrete sand, respectively. Three consolidation tests were conducted on each sand at relative densities which approximated the actual test densities. Thus, from Figures 12 and 13, the approximate density increase corresponding to a given overburden pressure application could be derived by interpolation. Density correction factors were added to the average density determined during placement for the middle portion of the specimen. Density values which take into account the increase due to the application of overburden pressure will be referred to hereafter as "adjusted" dry density values.

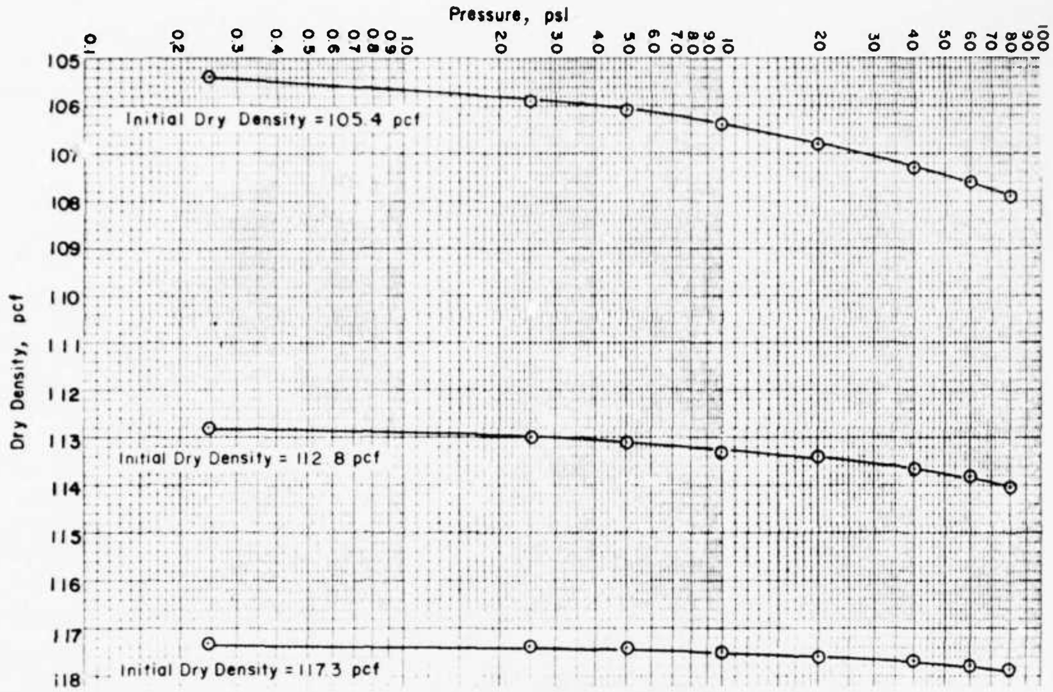

Figure 12. Consolidation test results for Platte River sand

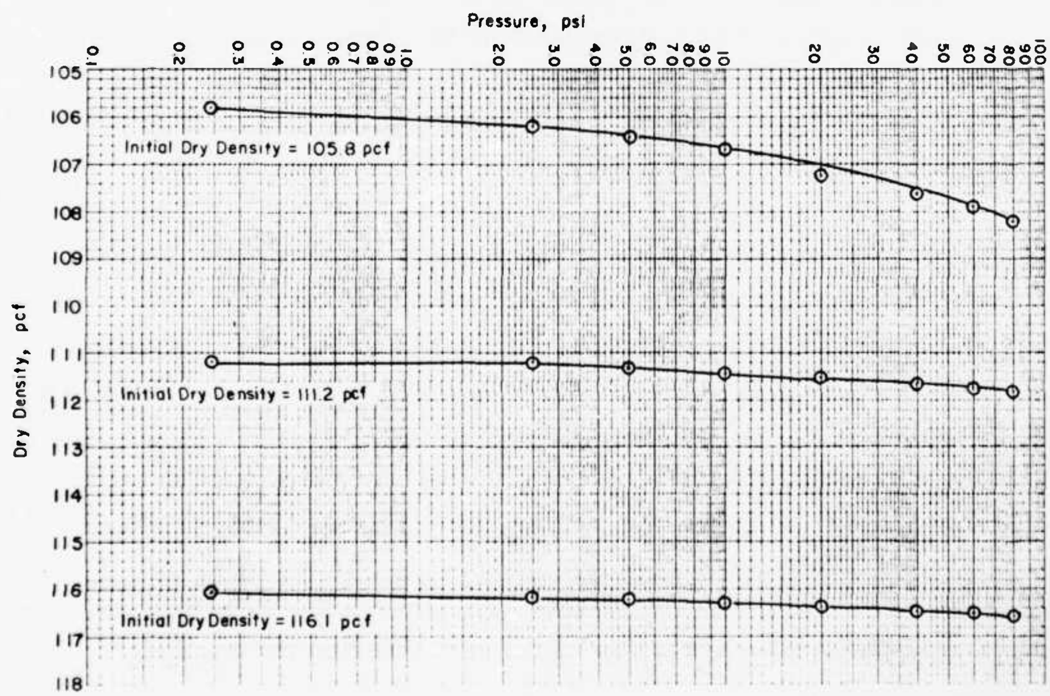

Figure 13. Consolidation test results for Standard Concrete sand

Submergence

23. Test specimens were submerged by the upward seepage of water from the perforated water hose buried in the filter beneath the specimen. The degree of saturation of a specimen so prepared ranged from 83 to 93 percent.[7]

PART IV: TEST RESULTS

24. The following paragraphs summarize the results of the individual tests on specimens constructed with Platte River sand and Standard Concrete sand. Three tests per sand were conducted and the test data are presented in Plates 1-6.

25. The plates contain plots of SPT blow counts per 6 in., SPT N-values, dry densities, and recovery versus depth in the tank. The dry density values reported are "placed" values (i.e., they do not reflect the effects of consolidation). Table 2 contains other pertinent information related to the test conditions, including the adjusted dry densities and the corresponding relative densities.

26. Attempts were made to obtain undisturbed samples through the center hole of each specimen. In some instances it was not possible to sample with the Hvorslev sampler, and the SPT was performed in the center hole.

Tests 27-32

Test 27

27. The specimen for Test 27 was constructed with Platte River sand by carefully placing the sand with the single-hose rainer. The specimen was prepared as loosely as possible by allowing the sand to flow from the hose to the specimen surface with a 1- to 2-in. drop. The average placed dry density in the middepth region was 105.1 pcf. The corresponding adjusted dry densities are given in Table 2. The N-values, depicted in Plate 1, increased with increasing overburden pressure. The last drives of the second and fourth holes drilled were not made since they were not to be used in the analysis.

Test 28

28. The second Platte River sand specimen was placed as described above, but with each lift densified using the vibrator mounted on the wooden platform. The average time of vibration was approximately 40 to 50 sec. This technique of densification was difficult to control as can

be observed from the plot of dry density versus depth in Plate 2. The average placed dry density in the middepth region was 112.3 pcf. Table 2 contains the adjusted dry densities at the corresponding levels of overburden pressure. The final drives of the three peripheral holes were not made since they were not to be used in the analysis.

Test 29

29. This was the final and densest specimen constructed with Platte River sand. The wood-mounted vibrator was not capable of producing the desired dry density; therefore, the same vibrator mounted to the 1/2-in.-thick steel plate and weighted down with three iron ingots was used (Figure 10). The period of vibration for each lift was 60 sec and the average middepth density obtained was 120.7 pcf. The adjusted density was assumed to be the same as the placed density, considering the results of the one-dimensional consolidation tests (Figure 12). Density homogeneity was difficult to control (Plate 3). The SPT N-values increased with increasing overburden pressure; however, for this test, the scatter in N-values was much greater than previously observed.

Test 30

30. This was the first specimen constructed with Standard Concrete sand. The method of preparation was identical with that used for Test 27. The average placed dry density in the middepth region was 105.8 pcf, and the corresponding adjusted dry densities at 10, 40, and 80 psi are given in Table 2. The density profile in Plate 4 exhibits scatter; however, the recorded penetration resistance was uniform with depth and increased with increasing pressure.

Test 31

31. The densest Standard Concrete sand specimen was constructed for Test 31. The average placed dry density was 119.8 pcf and was obtained by vibrating the specimen with the vibrator mounted on the steel plate. The iron ingots were again used for ballast and the time of vibration was 60 sec. The results of the one-dimensional consolidation tests indicated that adjustment for overburden pressure application at this density would be insignificant; hence, none was made. The variation in N-values (Plate 5) was similar to that observed for Test 29 and

was not great considering the large N-values. The center hole of this specimen was driven with the SPT sampler after several unsuccessful attempts to sample with the Hvorslev undisturbed sampler. Agreement between the results for the center hole and those for the peripheral hole drilled at the 10-psi testing pressure was good.

Test 32

32. A medium dense specimen was constructed for the final test with Standard Concrete sand. The vertical density profile was fairly homogeneous with depth (Plate 6), except at the very bottom of the specimen where it is observed to be denser. The average placed dry density in the middle region was 111.2 pcf. The corresponding adjusted dry densities are given in Table 2. Compaction was achieved with the vibrator mounted on the steel plate and with iron ingots for ballast. The individual lifts were limited to 1 sec of vibration at the maximum amplitude of the vibrator system. The recorded penetration resistance increased with increasing overburden pressure. The high values of penetration resistance recorded in the lower quadrant were due to the higher density lifts observed at the base of the specimen.

Summary

33. The six tests individually display a characteristic increase in penetration resistance known to occur with increasing overburden pressure and density. The relationships between density, penetration resistance, and overburden pressure developed in this study are presented in Figure 14 for Platte River sand and in Figure 15 for Standard Concrete sand.

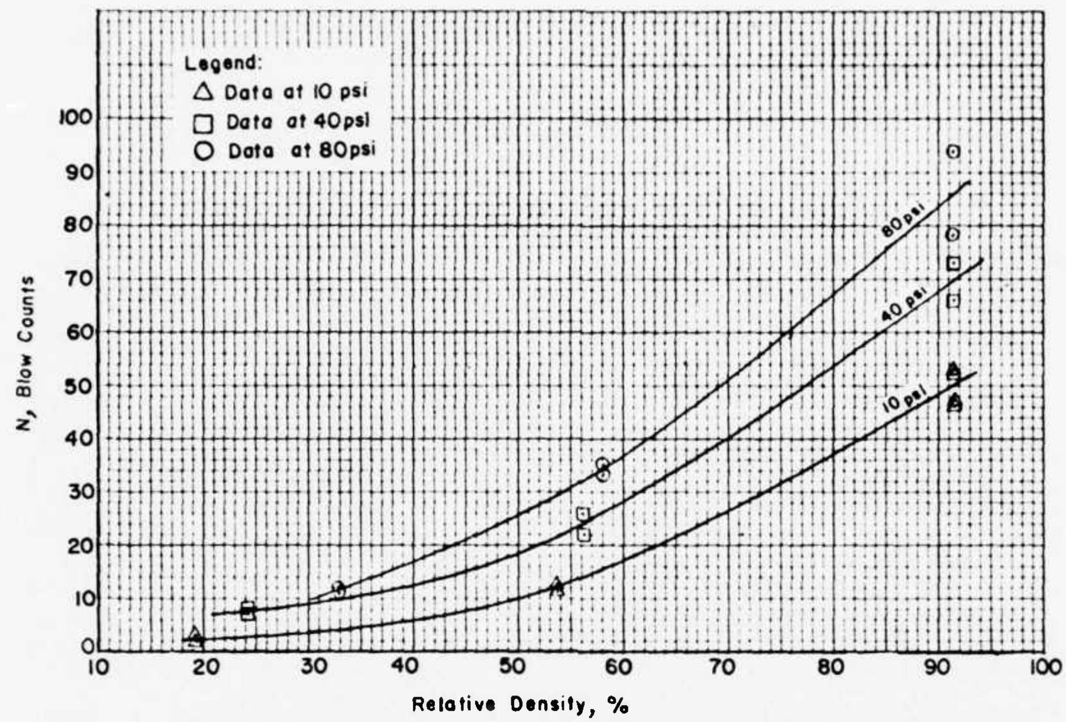

Figure 14. Relative density versus SPT N-values, Platte River sand

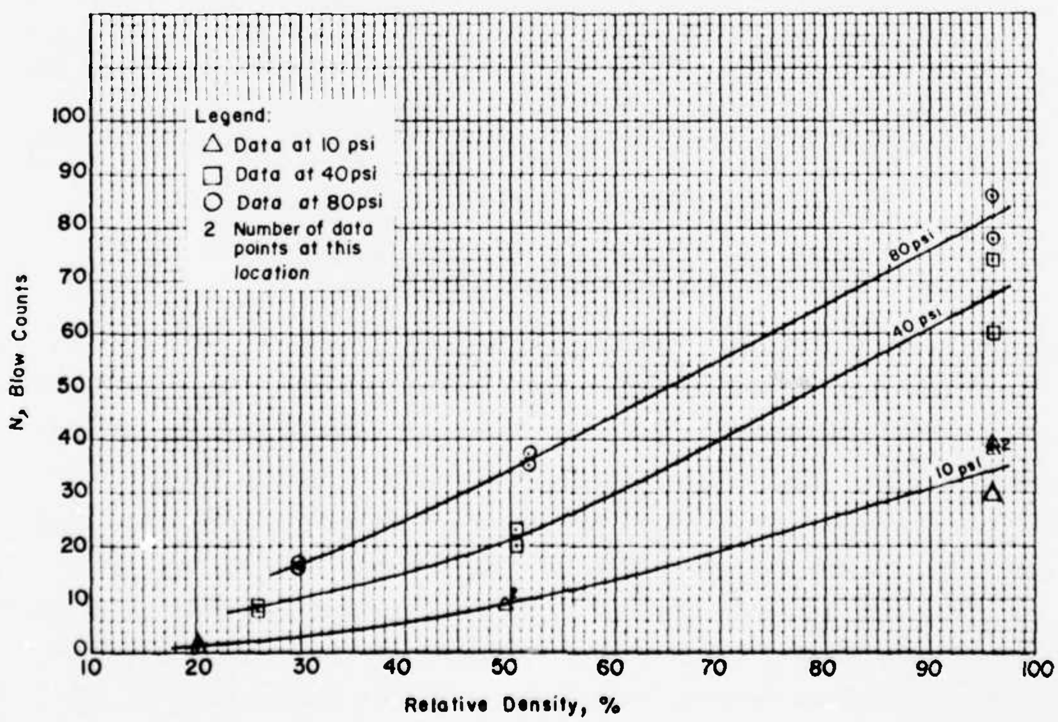

Figure 15. Relative density versus SPT N-values, Standard Concrete sand

PART V: DISCUSSION OF RESULTS

WES Data Comparison

34. The results of testing Platte River and Standard Concrete sands are compared in Figure 16. Very good agreement occurred at the

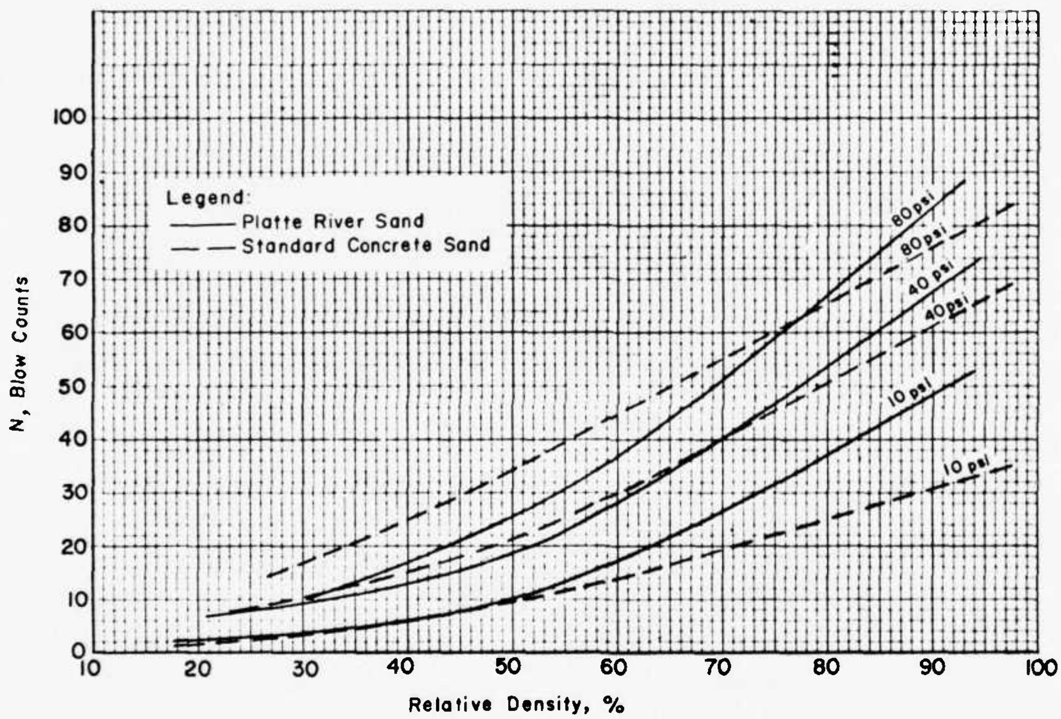

Figure 16. Comparison of Platte River sand and Standard Concrete sand data

40-psi testing pressure. The 10-psi data are in good agreement up to 60 percent relative density and then begin to diverge. The 80-psi curves are somewhat different for relative densities less than about 70 percent. Generally, the data obtained for both sands agree fairly well, and the differences that were observed may be due to differences in grain size distribution, mineralogy, and grain shape between the two sand types.

35. Previous WES data[7] obtained from testing Reid Bedford Model sand and Ottawa sand are displayed in Figure 17 along with the Platte River and Standard Concrete sand data. The data spread depicted in

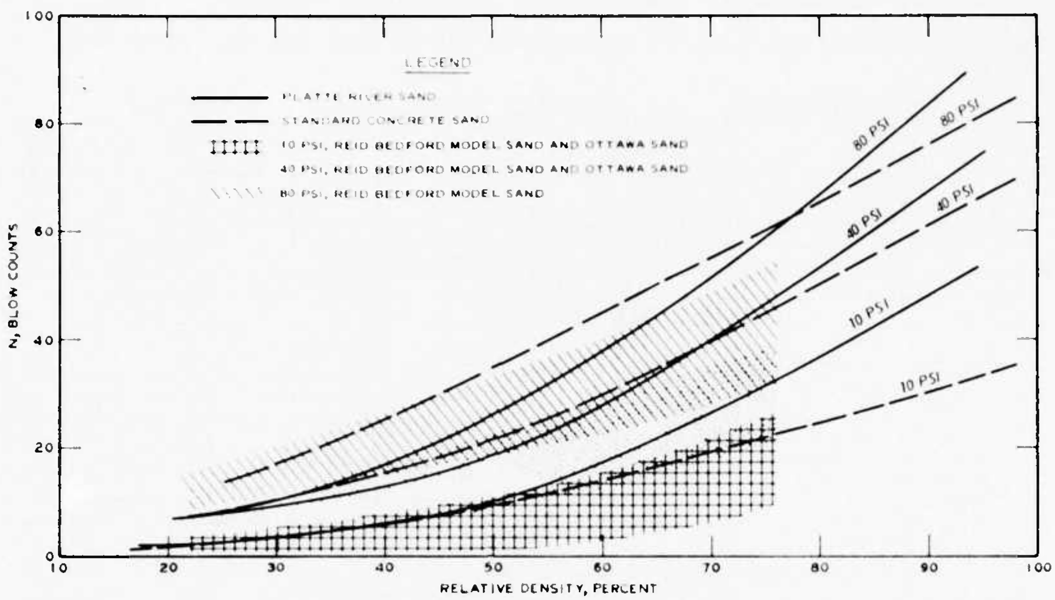

Figure 17. Comparison of Platte River, Standard Concrete, Reid Bedford Model, and Ottawa sand data

Figure 17 represents 24 tests on Reid Bedford Model sand and 2 tests on Ottawa sand. Several different methods of specimen preparation were used in the previous study, and it was then determined that the construction method influenced the penetration resistance.[7] The method of construction differed from the first test series to this present test series; therefore, the method of specimen preparation is an additional influence on the results which has not been considered in the analysis of these data. The results derived from testing Platte River sand and Standard Concrete sand generally lie in or slightly above the upper reaches of the band width formed by the Reid Bedford Model and Ottawa sand test data.

Comparisons with Previous Work by Others

36. In the 1950's at the Bureau of Reclamation, Gibbs and Holtz performed SPT's with sand similar to the Platte River sand used in this investigation.[2] The Platte River sand was in fact obtained by WES from

the Denver, Colo., area in an attempt to obtain a similar material. Figure 18 is a comparison of the Platte River sand and the Gibbs and

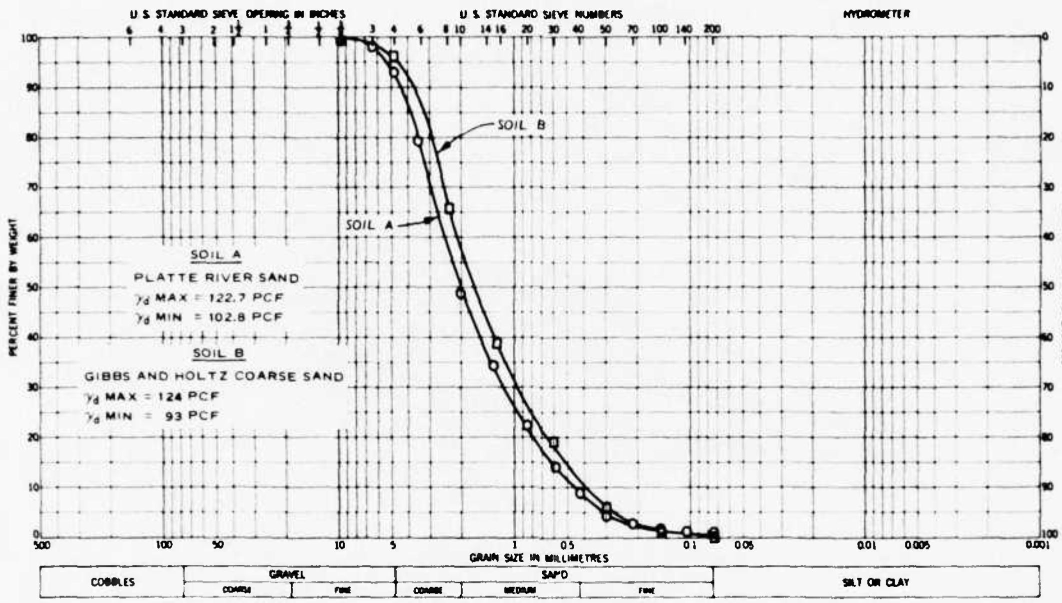

Figure 18. Comparison of grain size distributions of Gibbs and Holtz coarse sand and WES Platte River sand

Holtz sand. Practically speaking, the grain size distribution curves are identical; however, the minimum densities are not in agreement.

37. The minimum density reported for the WES Platte River sand was verified by check tests at WES and the Bureau of Reclamation to insure that differences in personnel, equipment, or procedures were not responsible for the difference in minimum densities. Both laboratories obtained values of 103 ±0.5 pcf (Appendix B). The difference between the Platte River sand and the Gibbs and Holtz sand must therefore be a function of some physical property or combination of properties other than grain size distribution. One purpose of the WES tests on Platte River sand was to examine the ability of the SPT to duplicate the Gibbs and Holtz correlation. Variations in test procedures and test equipment used by the two research facilities are given in Table 3. Figure 19 presents a comparison of the results of the present study with the Gibbs and Holtz correlation. It can be seen that the overall agreement is not

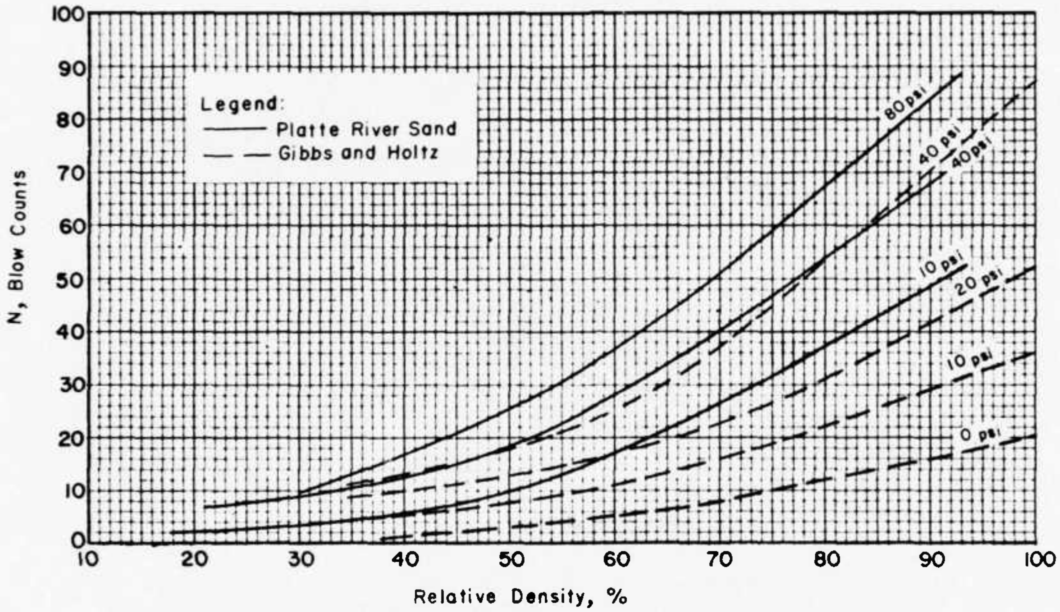

Figure 19. Comparison of WES Platte River sand data and Gibbs and Holtz correlation curves

good except at the 40-psi testing level and for relative densities less than about 60 percent. The WES results are slightly more conservative; i.e., for a given N-value, the WES curves for submerged specimens yield a lower value of relative density than the Gibbs and Holtz curves developed from dry tests (Table 3). Gibbs and Holtz also obtained results from testing submerged sands; however, they did not consider those results reliable.[2]

38. A comparison between the WES results on Platte River sand and the correlation curves by Bazaraa[11] is depicted in Figure 20. The Bazaraa curves are far more conservative than either the WES results or the Gibbs and Holtz correlation curves.

39. Similar comparisons between the Gibbs and Holtz and Bazaraa correlations were made with the WES Standard Concrete sand data. The Standard Concrete sand data display excellent agreement with the Gibbs and Holtz correlation curves (Figure 21). This agreement is unusual in

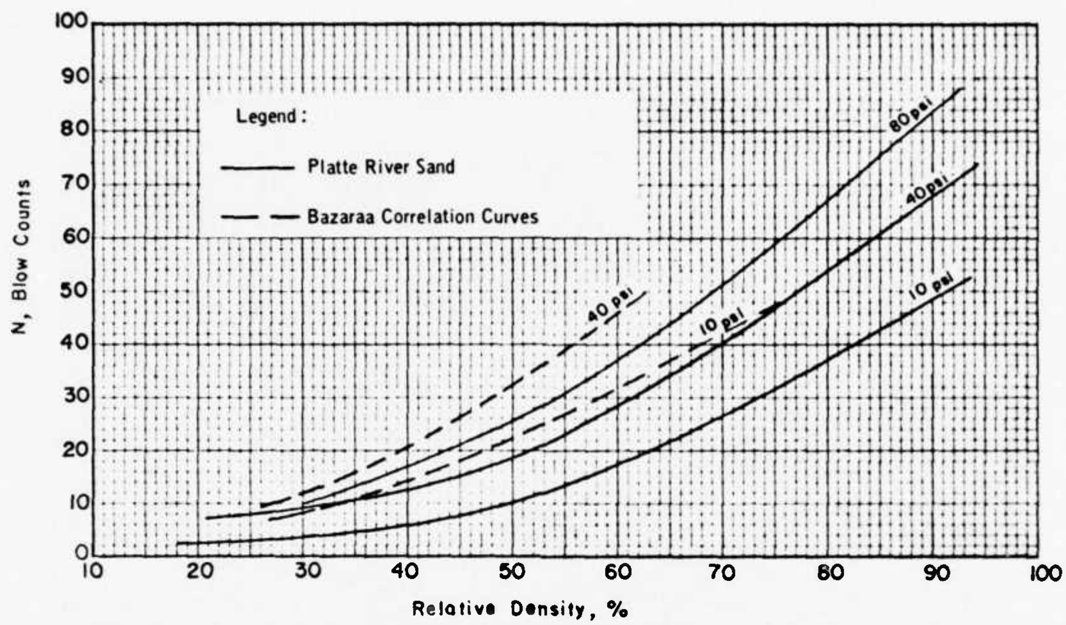

Figure 20. Comparison of WES Platte River sand data and Bazaraa correlation curves

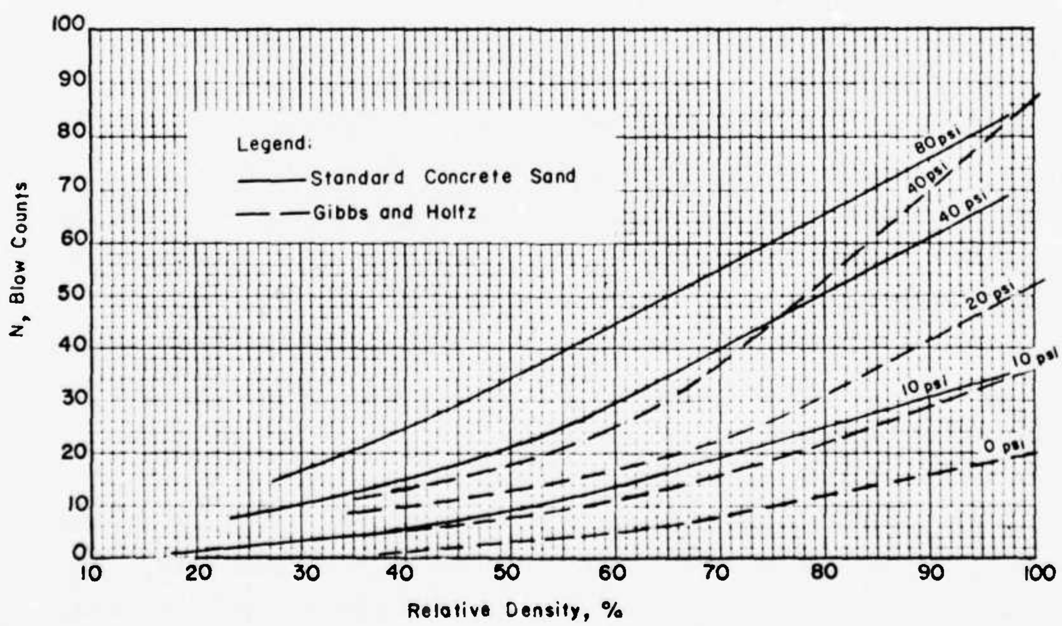

Figure 21. Comparison of WES Standard Concrete sand data and Gibbs and Holtz correlation curves

light of the dissimilarity between the two sand types. The comparison between the Standard Concrete sand data and the Bazaraa correlation curves (Figure 22) once again shows the Bazaraa correlations to be the more conservative.

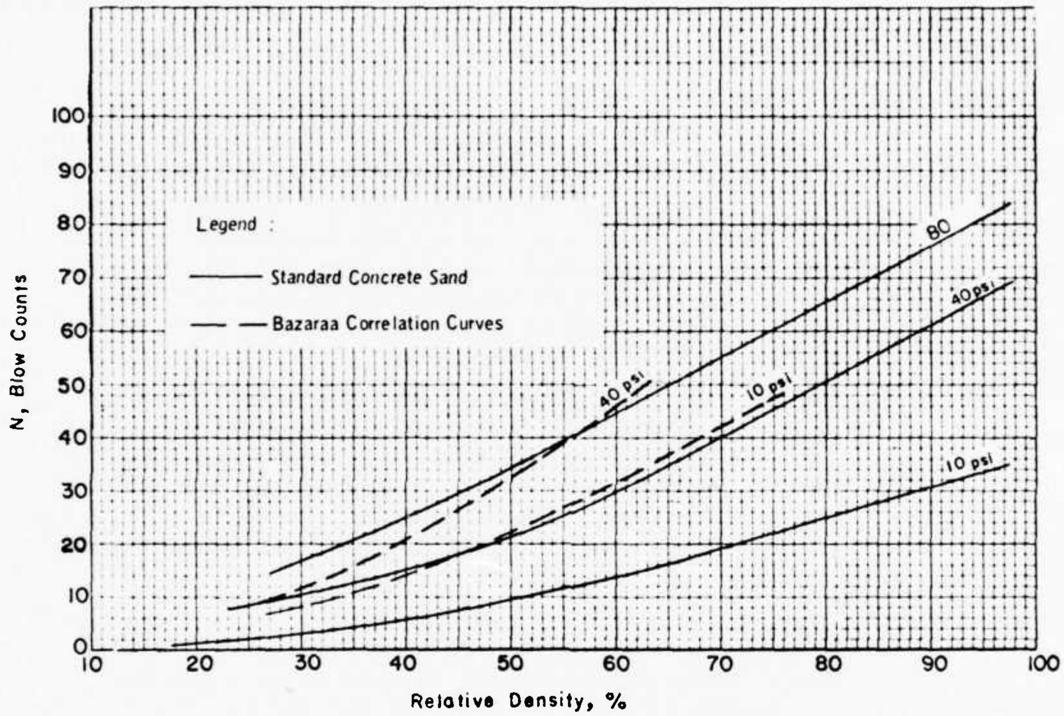

Figure 22. Comparison of WES Standard Concrete sand data and Bazaraa correlation curves

PART VI: STATISTICAL ANALYSIS OF WES DATA

Procedures

40. The multiple-regression computer program used for the analyses is capable of handling up to 75 variables. In general, the computer program has four basic steps in its operation:

a. Step 1. Values of the basic independent variables are input, and values of the combined variables are generated.

b. Step 2. The simple statistics (i.e., sum, mean, sum of the squares, variance, and standard deviation of each variable) are computed. A bivariant analysis is conducted (i.e., each variable is correlated with every other variable, one at a time). This indicates which of the variables are interrelated.

c. Step 3. For each dependent variable specified, the computer searches the independent variables (first taking one at a time, then two at a time, etc.) and lists the individual variables and combinations of variables that correlate best with the independent variable. Lists of variables that correlate best are termed models by the program.

d. Step 4. Based on the models generated, the independent and dependent variables are specified and a Doolittle matrix inversion technique is used to generate the regression equation of best fit through the data. This equation is in the form

$$y = b_0 + b_i x_i + b_{i+1} x_{i+1} \dots b_n x_n \qquad (2)$$

where

y = dependent variable

b_i = regression coefficient

x_i = independent variable

41. The computer program was written by Mr. James H. Goodnight[12] of the Department of Experimental Statistics, North Carolina State University. It was executed on a Honeywell GS-635 computer for this study.

42. Table 4 presents the complete data base obtained from testing Reid Bedford Model sand, Ottawa sand, Platte River sand, and Standard Concrete sand. In the earlier report,[7] the results of the statistical

analysis were reported for Reid Bedford Model and Ottawa sands. The data base used to derive an expression relating the various parameters excluded some of the test results since, for various reasons, they appeared invalid.[7] These results were from Tests 1, 3, 9, 10, 14, and 15, and they were also excluded from the present statistical analyses. The data base used for the statistical analyses herein is given in Table 5.

Results of the Statistical Analyses

43. In the previous report, an expression for relative density was derived based on the Reid Bedford Model sand and Ottawa sand data

$$D_R = 8.6 + 0.83\left[\left|222.2(N) + 2311.1 - 711.1(OCR) - 53.3(\bar{\sigma}_v)\right|\right]^{1/2} \qquad (3)$$

where

N = blow counts, blows per foot

OCR = overconsolidation ratio

$\bar{\sigma}_v$ = effective overburden pressure, psi

This expression fits the data with a coefficient of determination r^2 of 0.78 and has a standard deviation σ of 7.5 percent. The bracketed term raised to the 0.5 power is the x_i term of the equation $y = b_0 + b_i x_i$ discussed earlier. This formulation was slightly modified by a coefficient of uniformity term C_u to account for the differences in the four sands, and an analysis was performed on the data given in Table 5. The resulting expression

$$D_R = 12.2 + 0.75\left[\left|222(N) + 2311 - 711(OCR) - 53(\bar{\sigma}_v) - 50(C_u)^2\right|\right]^{1/2} \qquad (4)$$

produced the best fit, with a coefficient of determination of 0.85 and a standard deviation of 8.1 percent. This expression is biased by the distribution of data; i.e., there are far more Reid Bedford Model sand data than any other type. Also, because there are so few overconsolidation data, the reliability of using this expression to predict relative density values in overconsolidated deposits is questionable. Since there are an unequal number of data points for each sand, the "b-values" were determined independently using the above x_i term for each of the sands and for combinations of the data base. The resulting values are listed in Table 6 along with the number of data points, the coefficient of determination r^2, and the standard deviation σ. The extremely favorable correlations for Platte River sand and Standard Concrete sand resulted from good data over a wide range of relative densities. A combined analysis considering all but the overconsolidated data yielded an expression similar to that above

$$D_R = 11.7 + 0.76\left[\left|222(N) + 1600 - 53(\bar{\sigma}_v) - 50(C_u)^2\right|\right]^{1/2} \qquad (5)$$

Relative density predictions obtained using Equation 5 are compared with the observed laboratory values in Table 7. The column labeled "EXPECTED" contains those values predicted by Equation 5; the "OBSERVED" column contains known relative density values from the laboratory; and the "DIFFERENCE" column indicates the difference between the predicted and laboratory values.

44. A similar procedure of comparing predicted and laboratory values was employed for each of the four sands independently. The results are likewise presented in Tables 8-10 for the normally consolidated data derived from testing Reid Bedford Model sand, Platte River sand, and Standard Concrete sand. An analysis of the Ottawa sand data, by itself, was not believed valuable because of the limited number of data points and the small variation in relative density. Figure 23 contains plots showing the distribution of the differences between the predicted and observed relative densities given in Tables 7-10.

45. The significance of the statistical analysis is that it confirms the premise that relative density is interrelated to N-values, overburden pressure, overconsolidation ratio, and some term to account for a change in sand type. Equation 5 of this report adequately describes the data obtained from testing the normally consolidated specimens built from each of the four sands; however, it is not recommended as an equation to be used for every sand type and every circumstance in view of the scatter observed under optimum test conditions.

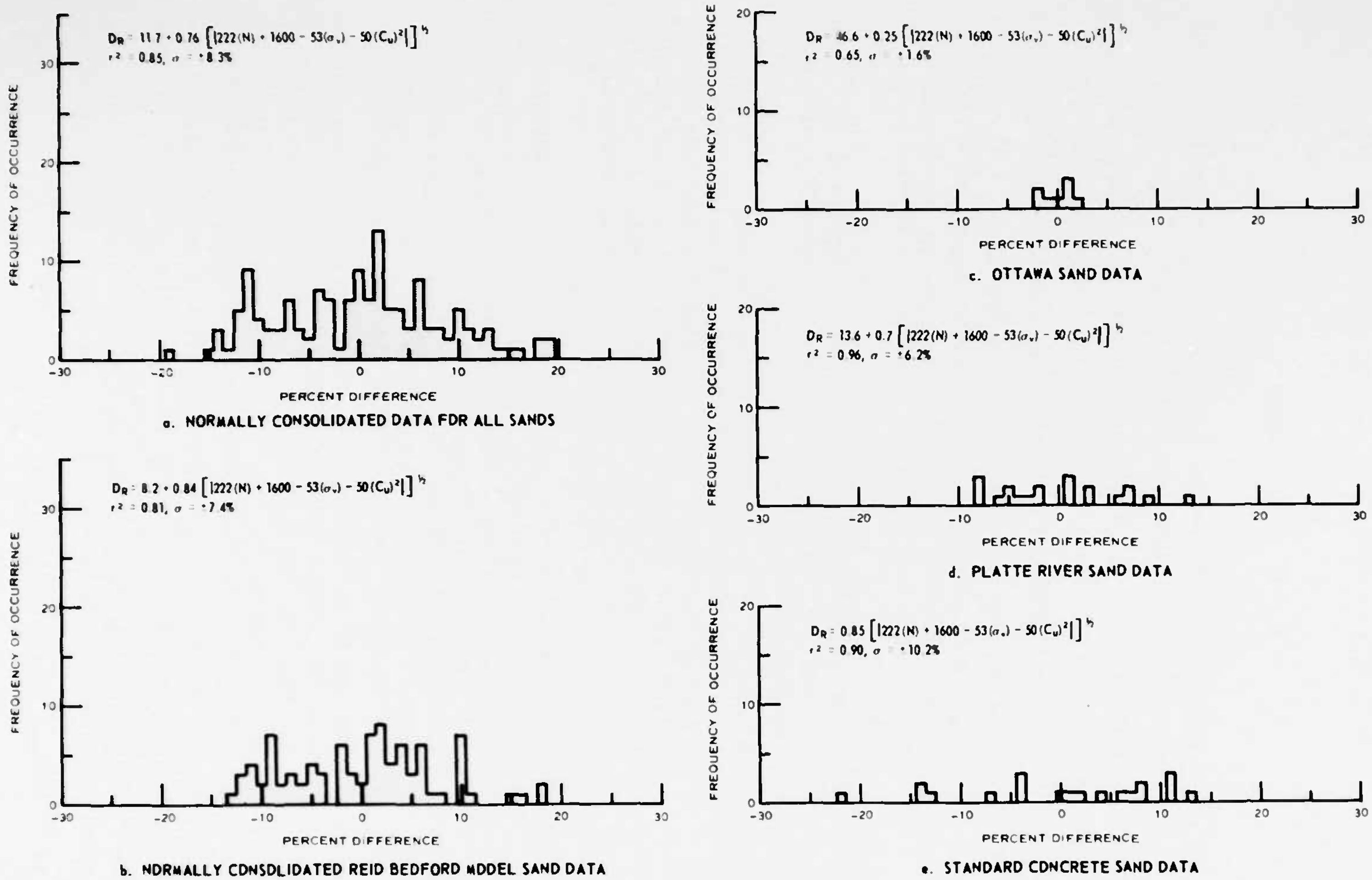

Figure 23. Distribution of the difference between predicted relative density and observed relative density

PART VII: CONCLUSIONS AND RECOMMENDATIONS

Conclusions

46. The conclusions stated are derived from this report and the previous WES report.[7] It is noted here that the effects of boundary conditions and rod length were not studied. Energy considerations have been very recently shown to be a substantial influencing factor on the results of the SPT.[13] This work has not evaluated the level of energy input or the response characteristics of the hammer-rod system.

- a. It is well established here and elsewhere[2,7,11] that penetration resistance is influenced by the density of the deposit and the level of effective overburden pressure.
- b. Under optimum laboratory test conditions, the SPT results for a given test specimen were reproducible within acceptable limits.
- c. A difference in the relationships between SPT N-values and relative density is observed in comparing the results reported for Platte River and Standard Concrete sands (Figure 16). Since all the test procedures and conditions were the same, except sand type, it seems reasonable to conclude that the variation in results was generated by differences in the two sands tested.
- d. A comparison of all four sands is made in Figure 17. The Platte River and Standard Concrete sand results generally lie near or slightly above the upper boundary of the Reid Bedford Model and Ottawa sand band width.[7] An exception to this is the 80-psi Platte River sand results. Two factors are thought responsible for the difference: (1) method of specimen preparation and (2) sand type.
- e. The spread of data derived from testing four sands under optimum laboratory conditions suggests that establishing a simplified family of curves correlating SPT N-values, relative density, and overburden pressure for all cohesionless soils under all conditions is not warranted.
- f. The expressions derived from the statistical analysis are not recommended for general use. The equations are based on data derived under optimum conditions and do not adequately address the variability of subsurface conditions found in the field. Water table conditions, overconsolidation, and length and weight of drill rods were not adequately studied.

Recommendations

47. Evidence from this and previous work indicates that the effects of soil type and overconsolidation need to be examined. The principal factor not adequately addressed by this study is the overconsolidation ratio. The effects of length and weight of drill rods have not been completely resolved and might provide another area for investigation, although the effects are believed to be of the second order.[2]

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Table 1

Summary of Tests

Test	Material	γ_d Placed pcf	D_R Placed percent	Preparation Method	Overburden Pressure Sequence psi	Overconsolidation Ratio	Undisturbed Sample	Water Table Condition	Remarks
1	Reid Bedford Model sand	95.4	40.9	Rotating rainer	40	1	None	Submerged	Data considered unreliable
2		95.4	40.9		10-40-80	1	Center hole	Submerged	--
3		94.4	35.1		5-40-80	1		Drained	--
4		91.6	18.3		10-40-80	1		Submerged	--
5		98.5	57.6		10-40	1			No data at 80 psi: water bag ruptured
6		97.7	53.4		10-40-80	3			--
7		94.4	35.2		10-40-80	3			--
8		95.5	41.3		40	1	None		Check test for Test 1
9		93.3	28.9			1			Rained into water
10		99.9	65.1	Rotating rainer; rodded		1			Rained into water; rodded
11		93.2	28.2	Rotating rainer		1			--
12		100.9	70.5	Rotating rainer					--
13		96.0	44.3	Rotating rainer					--
14		100.4	67.7	Rotating rainer; rodded					Rained into water; rodded
15		98.9	60.2	Rotating rainer; rodded					Rained into water; rodded
16		92.2	21.9	Rotating rainer	10				--
17		101.4	72.8	Rotating rainer; tamped	10				Manual tamping with 1-ft-square plate
18		101.5	73.5	Rotating rainer; tamped	80				Manual tamping with 1-ft-square plate
19		101.3	72.5	Single-hose rainer	40				--
20		95.4	40.3	Circular rainer	40				--
21		93.7	30.8		40				--
22		97.0	49.7		80		Center hole		--
23		90.5	11.6		80		Center hole		--

(Continued)

Table 1 (Concluded)

Test	Material	γ_d Placed pcf	D_R Placed percent	Preparation Method	Overburden Pressure Sequence psi	Overconsolidation Ratio	Undisturbed Sample	Water Table Condition	Remarks
24	Reid Bedford Model sand	100.5	73.3	Circular rainer	80	1	Center hole	Submerged	--
25	Ottawa sand	100.9	53.1	Circular rainer	10-40				--
26	Ottawa sand	101.5	56.8	Circular rainer	10-40				--
27	Platte River sand	105.1	13.5	Single-hose rainer	10-40-80				--
28	Platte River sand	112.3	52.2	Single-hose rainer; vibrated					--
29	Platte River sand	120.7	91.4	Single-hose rainer; vibrated					--
30	Standard Concrete sand	105.8	14.2	Single-hose rainer					--
31	Standard Concrete sand	119.8	95.9	Single-hose rainer; vibrated					--
32	Standard Concrete sand	111.2	48.1	Single-hose rainer; vibrated					--

Table 2

Summary of Data Points for Platte River Sand and Standard Concrete Sand

Test	D_R* Percent	γ_d** Adjusted pcf	Sand Type†	N	Effective Overburden Pressure psi	Specimen Preparation
27	19.2	106.1	PRS	3	10	Single-hose rainer
27	19.2	106.1	PRS	2	10	
27	24.2	107.0	PRS	7	40	
27	24.2	107.0	PRS	8	40	
27	32.9	108.6	PRS	11	80	
27	32.9	108.6	PRS	12	80	
28	53.7	112.8	PRS	11	10	Single-hose rainer; vibrated (wooden)
28	53.7	112.8	PRS	12	10	
28	56.2	113.1	PRS	22	40	
28	56.2	113.1	PRS	26	40	
28	58.1	113.5	PRS	33	80	
28	58.1	113.5	PRS	35	80	
29	91.4	120.7	PRS	53	10	Single-hose rainer; vibrated (steel)
29	91.4	120.7	PRS	52	10	
29	91.4	120.7	PRS	47	10	
29	91.4	120.7	PRS	46	10	
29	91.4	120.7	PRS	73	40	
29	91.4	120.7	PRS	66	40	
29	91.4	120.7	PRS	94	80	
29	91.4	120.7	PRS	78	80	
30	20.1	106.7	SCS	2	10	Single-hose rainer
30	20.1	106.7	SCS	1	10	
30	25.9	107.6	SCS	9	40	
30	25.9	107.6	SCS	8	40	
30	29.7	108.2	SCS	16	80	
30	29.7	108.2	SCS	17	80	
31	95.9	119.8	SCS	38	10	Single-hose rainer; vibrated (steel)
31	95.9	119.8	SCS	38	10	
31	95.9	119.8	SCS	30	10	
31	95.9	119.8	SCS	39	10	
31	95.9	119.8	SCS	60	40	
31	95.9	119.8	SCS	74	40	
31	95.9	119.8	SCS	78	80	
31	95.9	119.8	SCS	86	80	
32	49.3	111.4	SCS	9	10	
32	49.3	111.4	SCS	9	10	
32	50.5	111.6	SCS	20	40	
32	50.5	111.6	SCS	23	40	
32	51.7	111.8	SCS	35	80	
32	51.7	111.8	SCS	37	80	

* Relative density corresponding to the adjusted dry density.

** Adjusted to account for an increase in density due to an application of overburden pressure.

† PRS denotes Platte River sand; SCS denotes Standard Concrete sand.

Table 3

Variations in Techniques and Equipment Between the Bureau of Reclamation and WES SPT Studies

Bureau of Reclamation Tests	WES Tests
1. Applied overburden pressure by means of rigid plates and springs	Applied overburden pressure with flexible, fiberglass-reinforced rubber water bag
2. Soil container was a solid wall tank, 3 ft 1-1/2 in. in diameter, with sidewall friction present*	Soil container was a layered system of alternating steel and rubber rings to provide flexibility in the vertical direction to avoid sidewall friction
3. Cathead with an unstated number of turns was used	Trip hammer was used
4. Penetration tests were made through six holes in the loading plate	Penetration tests were made through a maximum of four holes
5. Sand placement was by lifts compacted with a mechanical tamper	Various sand placement techniques during the first series. Compaction by vibrator during the second series
6. Testing performed on submerged and dry specimens; recommendations were developed from the dry sand results	Testing performed on submerged specimens
7. Rod lengths of 0, 32, and 65 ft were studied	Rod lengths were limited. The minimum length was 5 ft and the maximum length was 11 ft
8. A, B, and N rods were incorporated in the study	N rods were used exclusively

* Earth pressure cells were used to obtain intergranular vertical stress.

Table 4

Complete Statistical Data Base for All WES-Derived Data Developed by WES

TEST NO.	SAND TYPE	OCR	HOLE NO.	SEQUENCE	CORRECTED DRY DENSITY (PCF)	RELATIVE DENSITY (PERCENT)	VERTICAL STRESS (PSI)	DEPTH (FEET)	SPT N VALUE	RECOVERY (PERCENT)	D(10) MM	D(50) MM	D(60) MM
1.00	1.00	1.00	4.00	1.00	96.20	45.40	40.00	2.50	25.00	1.00	0.16	0.25	0.26
1.00	1.00	1.00	4.00	1.00	96.20	45.40	40.00	4.00	31.00	1.00	0.16	0.25	0.26
1.00	1.00	1.00	1.00	2.00	96.20	45.40	40.00	2.50	50.00	1.00	0.16	0.25	0.26
1.00	1.00	1.00	[illegible]	2.00	96.20	45.40	40.00	4.00	44.00	1.00	0.16	0.25	0.26
1.00	1.00	1.00	2.00	3.00	96.20	45.40	40.00	2.50	34.00	1.00	0.16	0.25	0.26
1.00	1.00	1.00	2.00	3.00	96.20	45.40	40.00	4.00	33.00	1.00	0.16	0.25	0.26
1.00	1.00	1.00	3.00	4.00	96.20	45.40	40.00	2.50	43.00	1.00	0.16	0.25	0.26
1.00	1.00	1.00	3.00	4.00	96.20	45.40	40.00	4.00	61.00	1.00	0.16	0.25	0.26
2.00	1.00	1.00	3.00	2.00	95.90	43.80	10.00	2.50	6.00	63.30	0.16	0.25	0.26
2.00	1.00	1.00	3.00	2.00	95.90	43.80	10.00	4.00	9.00	66.70	0.16	0.25	0.26
2.00	1.00	1.00	2.00	3.00	96.20	45.30	40.00	2.50	15.00	73.30	0.16	0.25	0.26
2.00	1.00	1.00	2.00	3.00	96.20	45.30	40.00	4.00	20.00	73.30	0.16	0.25	0.26
2.00	1.00	1.00	1.00	4.00	96.30	46.10	80.00	2.50	25.00	66.70	0.16	0.25	0.26
2.00	1.00	1.00	1.00	4.00	96.30	46.10	80.00	4.00	31.00	66.70	0.16	0.25	0.26
3.00	1.00	1.00	1.00	2.00	94.70	36.90	5.00	2.50	4.00	1.00	0.16	0.25	0.26
3.00	1.00	1.00	1.00	2.00	94.70	36.90	5.00	4.00	4.00	1.00	0.16	0.25	0.26
3.00	1.00	1.00	2.00	3.00	95.40	40.90	40.00	2.50	15.00	1.00	0.16	0.25	0.26
3.00	1.00	1.00	2.00	3.00	95.40	40.90	40.00	4.00	12.00	1.00	0.16	0.25	0.26
3.00	1.00	1.00	3.00	4.00	95.50	41.40	80.00	2.50	23.00	1.00	0.16	0.25	0.26
3.00	1.00	1.00	3.00	4.00	95.50	41.40	80.00	4.00	19.00	1.00	0.16	0.25	0.26
4.00	1.00	1.00	2.00	2.00	92.60	24.30	10.00	2.50	3.00	1.00	0.16	0.25	0.26
4.00	1.00	1.00	2.00	2.00	92.60	24.30	10.00	4.00	3.00	1.00	0.16	0.25	0.26
4.00	1.00	1.00	1.00	3.00	93.20	27.80	40.00	2.50	6.00	1.00	0.16	0.25	0.26
4.00	1.00	1.00	1.00	3.00	93.20	27.80	40.00	4.00	9.00	1.00	0.16	0.25	0.26
4.00	1.00	1.00	3.00	4.00	93.40	29.50	80.00	2.50	14.00	1.00	0.16	0.25	0.26
4.00	1.00	1.00	3.00	4.00	93.40	29.50	80.00	4.00	16.00	1.00	0.16	0.25	0.26
5.00	1.00	1.00	2.00	2.00	98.70	59.00	10.00	2.50	13.00	1.00	0.16	0.25	0.26
5.00	1.00	1.00	2.00	2.00	98.70	59.00	10.00	4.00	11.00	1.00	0.16	0.25	0.26
5.00	1.00	1.00	3.00	3.00	98.80	59.70	40.00	2.50	23.00	1.00	0.16	0.25	0.26
5.00	1.00	1.00	3.00	3.00	98.80	59.70	40.00	4.00	22.00	1.00	0.16	0.25	0.26
6.00	1.00	3.00	2.00	2.00	98.20	56.30	10.00	2.50	12.00	1.00	0.16	0.25	0.26
6.00	1.00	3.00	2.00	2.00	98.20	56.30	10.00	4.00	12.00	1.00	0.16	0.25	0.26
6.00	1.00	3.00	3.00	3.00	98.40	57.30	40.00	2.50	25.00	84.00	0.16	0.25	0.26
6.00	1.00	3.00	3.00	3.00	98.40	57.30	40.00	4.00	27.00	88.00	0.16	0.25	0.26
6.00	1.00	3.00	1.00	4.00	98.70	59.00	80.00	2.50	38.00	88.00	0.16	0.25	0.26
6.00	1.00	3.00	1.00	4.00	98.70	59.00	80.00	4.00	38.00	88.00	0.16	0.25	0.26
7.00	1.00	3.00	1.00	2.00	94.90	30.00	10.00	2.50	5.00	88.00	0.16	0.25	0.26

(Continued)

Table 4 (Continued)

7.00	1.00	3.00	1.00	2.00	94.90	38.00	10.00	4.00	4.00	84.00	0.16	0.25	0.26
7.00	1.00	3.00	2.00	3.00	95.20	39.70	40.00	2.50	16.00	92.00	0.16	0.25	0.26
7.00	1.00	3.00	2.00	3.00	95.20	39.70	40.00	4.00	16.00	84.00	0.16	0.25	0.26
7.00	1.00	3.00	3.00	4.00	95.40	40.90	80.00	2.50	27.00	92.00	0.16	0.25	0.26
7.00	1.00	3.00	3.00	4.00	95.40	40.90	80.00	4.00	30.00	08.00	0.16	0.25	0.26
8.00	1.00	1.00	4.00	1.00	96.30	45.70	40.00	2.50	9.00	1.00	0.16	0.25	0.26
8.00	1.00	1.00	4.00	1.00	96.30	45.70	40.00	4.00	13.00	1.00	0.16	0.25	0.26
8.00	1.00	1.00	1.00	2.00	96.30	45.70	40.00	2.50	12.00	1.00	0.16	0.25	0.26
8.00	1.00	1.00	1.00	2.00	96.30	45.70	40.00	4.00	13.00	1.00	0.16	0.25	0.26
8.00	1.00	1.00	2.00	3.00	96.30	45.70	40.00	2.50	12.00	1.00	0.16	0.25	0.26
8.00	1.00	1.00	2.00	3.00	96.30	45.70	40.00	4.00	13.00	1.00	0.16	0.25	0.26
8.00	1.00	1.00	3.00	4.00	96.30	45.70	40.00	2.50	14.00	1.00	0.16	0.25	0.26
8.00	1.00	1.00	3.00	4.00	96.30	45.70	40.00	4.00	17.00	1.00	0.16	0.25	0.26
9.00	1.00	1.00	4.00	1.00	94.10	33.40	40.00	2.50	6.00	56.80	0.16	0.25	0.26
9.00	1.00	1.00	4.00	1.00	94.10	33.40	40.00	4.00	6.00	80.80	0.16	0.25	0.26
9.00	1.00	1.00	1.00	2.00	94.10	33.40	40.00	2.50	7.00	48.80	0.16	0.25	0.26
9.00	1.00	1.00	1.00	2.00	94.10	33.40	40.00	4.00	6.00	40.80	0.16	0.25	0.26
9.00	1.00	1.00	2.00	3.00	94.10	33.40	40.00	2.50	7.00	40.80	0.16	0.25	0.26
9.00	1.00	1.00	2.00	3.00	94.10	33.40	40.00	4.00	7.00	73.80	0.16	0.25	0.26
10.00	1.00	1.00	4.00	1.00	100.00	65.80	40.00	2.50	41.00	68.00	0.16	0.25	0.26
10.00	1.00	1.00	4.00	1.00	100.00	65.80	40.00	4.00	38.00	78.40	0.16	0.25	0.26
10.00	1.00	1.00	1.00	2.00	100.00	65.80	40.00	2.50	30.00	81.60	0.16	0.25	0.26
10.00	1.00	1.00	1.00	2.00	100.00	65.80	40.00	4.00	32.00	72.00	0.16	0.25	0.26
10.00	1.00	1.00	2.00	3.00	100.00	65.80	40.00	2.50	41.00	84.00	0.16	0.25	0.26
10.00	1.00	1.00	2.00	3.00	100.00	65.80	40.00	4.00	39.00	84.00	0.16	0.25	0.26
11.00	1.00	1.00	4.00	1.00	94.40	35.10	40.00	2.50	5.00	92.00	0.16	0.25	0.26
11.00	1.00	1.00	4.00	1.00	94.40	35.10	40.00	4.00	7.00	88.00	0.16	0.25	0.26
11.00	1.00	1.00	1.00	2.00	94.40	35.10	40.00	2.50	7.00	88.00	0.16	0.25	0.26
11.00	1.00	1.00	1.00	2.00	94.40	35.10	40.00	4.00	9.00	87.20	0.16	0.25	0.26
11.00	1.00	1.00	2.00	3.00	94.40	35.10	40.00	2.50	8.00	90.40	0.16	0.25	0.26
11.00	1.00	1.00	2.00	3.00	94.40	35.10	40.00	4.00	0.00	90.40	0.16	0.25	0.26
12.00	1.00	1.00	4.00	1.00	101.10	71.50	40.00	2.50	35.00	84.00	0.16	0.25	0.26
12.00	1.00	1.00	4.00	1.00	101.10	71.50	40.00	4.00	32.00	72.00	0.16	0.25	0.26
12.00	1.00	1.00	1.00	2.00	101.10	71.50	40.00	2.50	27.00	72.00	0.16	0.25	0.26
12.00	1.00	1.00	1.00	2.00	101.10	71.50	40.00	4.00	31.00	72.00	0.16	0.25	0.26
12.00	1.00	1.00	2.00	3.00	101.10	71.50	40.00	2.50	30.00	76.00	0.16	0.25	0.26
12.00	1.00	1.00	2.00	3.00	101.10	71.50	40.00	4.00	32.00	80.00	0.16	0.25	0.26
13.00	1.00	1.00	4.00	1.00	96.70	40.20	40.00	2.50	8.00	76.00	0.16	0.25	0.26
13.00	1.00	1.00	4.00	1.00	96.70	48.20	40.00	4.00	8.00	70.40	0.16	0.25	0.26
13.00	1.00	1.00	1.00	2.00	96.70	48.20	40.00	2.50	9.00	72.00	0.16	0.25	0.26
13.00	1.00	1.00	1.00	2.00	96.70	48.20	40.00	4.00	9.00	72.00	0.16	0.25	0.26
13.00	1.00	1.00	2.00	3.00	96.70	48.20	40.00	2.50	12.00	74.40	0.16	0.25	0.26
13.00	1.00	1.00	2.00	3.00	96.70	40.20	40.00	4.00	11.00	60.00	0.16	0.25	0.26

(Continued)

Table 4 (Continued)

14.00	1.00	1.00	4.00	1.00	100.60	68.80	40.00	2.50	34.00	77.60	0.16	0.25	0.26
14.00	1.00	1.00	4.00	1.00	100.60	68.80	40.00	4.00	32.00	77.60	0.16	0.25	0.26
14.00	1.00	1.00	1.00	2.00	100.60	68.80	40.00	2.50	29.00	70.40	0.16	0.25	0.26
14.00	1.00	1.00	1.00	2.00	100.60	68.80	40.00	4.00	37.00	76.00	0.16	0.25	0.26
15.00	1.00	1.00	4.00	1.00	99.50	63.20	40.00	2.50	25.00	81.60	0.16	0.25	0.26
15.00	1.00	1.00	4.00	1.00	99.50	63.20	40.00	4.00	25.00	69.60	0.16	0.25	0.26
15.00	1.00	1.00	1.00	2.00	99.50	63.20	40.00	2.50	27.00	77.60	0.16	0.25	0.26
15.00	1.00	1.00	1.00	2.00	99.50	63.20	40.00	4.00	30.00	80.00	0.16	0.25	0.26
16.00	1.00	1.00	4.00	1.00	93.00	27.10	10.00	2.50	1.00	60.00	0.16	0.25	0.26
16.00	1.00	1.00	4.00	1.00	93.00	27.10	10.00	4.00	1.00	60.00	0.16	0.25	0.26
16.00	1.00	1.00	1.00	2.00	93.00	27.10	10.00	2.50	1.00	52.00	0.16	0.25	0.26
16.00	1.00	1.00	1.00	2.00	93.00	27.10	10.00	4.00	1.00	44.00	0.16	0.25	0.26
17.00	1.00	1.00	4.00	1.00	101.50	73.20	10.00	2.50	17.00	78.40	0.16	0.25	0.26
17.00	1.00	1.00	4.00	1.00	101.50	73.20	10.00	4.00	24.00	68.80	0.16	0.25	0.26
17.00	1.00	1.00	1.00	2.00	101.50	73.20	10.00	2.50	15.00	72.00	0.16	0.25	0.26
17.00	1.00	1.00	1.00	2.00	101.50	73.20	10.00	4.00	19.00	70.40	0.16	0.25	0.26
17.00	1.00	1.00	2.00	3.00	101.50	73.20	10.00	2.50	15.00	75.20	0.16	0.25	0.26
17.00	1.00	1.00	2.00	3.00	101.50	73.20	10.00	4.00	19.00	68.80	0.16	0.25	0.26
18.00	1.00	1.00	4.00	1.00	101.70	74.40	80.00	2.50	33.00	67.20	0.16	0.25	0.26
18.00	1.00	1.00	4.00	1.00	101.70	74.40	80.00	4.00	42.00	72.80	0.16	0.25	0.26
18.00	1.00	1.00	1.00	2.00	101.70	74.40	80.00	2.50	39.00	80.80	0.16	0.25	0.26
18.00	1.00	1.00	1.00	2.00	101.70	74.40	80.00	4.00	45.00	70.20	0.16	0.25	0.26
18.00	1.00	1.00	2.00	3.00	101.70	74.40	80.00	2.50	46.00	74.80	0.16	0.25	0.26
18.00	1.00	1.00	2.00	3.00	101.70	74.40	80.00	4.00	49.00	83.20	0.16	0.25	0.26
19.00	1.00	1.00	4.00	1.00	101.50	73.50	40.00	2.50	20.00	78.40	0.16	0.25	0.26
19.00	1.00	1.00	4.00	1.00	101.50	73.50	40.00	4.00	23.00	80.00	0.16	0.25	0.26
19.00	1.00	1.00	1.00	2.00	101.50	73.50	40.00	2.50	27.00	75.20	0.16	0.25	0.26
19.00	1.00	1.00	1.00	2.00	101.50	73.50	40.00	4.00	24.00	76.00	0.16	0.25	0.26
19.00	1.00	1.00	2.00	3.00	101.50	73.50	40.00	2.50	26.00	68.80	0.16	0.25	0.26
19.00	1.00	1.00	2.00	3.00	101.50	73.50	40.00	4.00	26.00	70.40	0.16	0.25	0.26
20.00	1.00	1.00	4.00	1.00	96.20	45.30	40.00	2.50	8.00	78.40	0.16	0.25	0.26
20.00	1.00	1.00	4.00	1.00	96.20	45.30	40.00	4.00	9.00	70.20	0.16	0.25	0.26
20.00	1.00	1.00	1.00	2.00	96.20	45.30	40.00	2.50	13.00	71.20	0.16	0.25	0.26
20.00	1.00	1.00	1.00	2.00	96.20	45.30	40.00	4.00	10.00	65.60	0.16	0.25	0.26
20.00	1.00	1.00	3.00	3.00	96.20	45.30	40.00	2.50	12.00	74.40	0.16	0.25	0.26
20.00	1.00	1.00	3.00	3.00	96.20	45.30	40.00	4.00	15.00	67.20	0.16	0.25	0.26
20.00	1.00	1.00	2.00	4.00	96.20	45.30	40.00	2.50	13.00	69.60	0.16	0.25	0.26
20.00	1.00	1.00	2.00	4.00	96.20	45.30	40.00	4.00	12.00	66.40	0.16	0.25	0.26
21.00	1.00	1.00	4.00	1.00	94.80	37.60	40.00	2.50	8.00	76.80	0.16	0.25	0.26
21.00	1.00	1.00	4.00	1.00	94.80	37.60	40.00	4.00	11.00	80.80	0.16	0.25	0.26
21.00	1.00	1.00	1.00	2.00	94.80	37.60	40.00	2.50	8.00	72.80	0.16	0.25	0.26
21.00	1.00	1.00	1.00	2.00	94.80	37.60	40.00	4.00	9.00	66.40	0.16	0.25	0.26
21.00	1.00	1.00	2.00	3.00	94.80	37.60	40.00	2.50	9.00	73.80	0.16	0.25	0.26

(Continued)

Table 4 (Continued)

21.00	1.00	1.00	2.00	3.00	94.80	37.60	40.00	4.00	11.00	1.00	0.16	0.25	0.26
22.00	1.00	1.00	1.00	2.00	97.70	53.80	80.00	2.50	20.00	79.20	0.16	0.25	0.26
22.00	1.00	1.00	1.00	2.00	97.70	53.80	80.00	4.00	22.00	71.20	0.16	0.25	0.26
22.00	1.00	1.00	2.00	3.00	97.70	53.80	80.00	2.50	20.00	72.80	0.16	0.25	0.26
22.00	1.00	1.00	2.00	3.00	97.70	53.80	80.00	4.00	20.00	70.40	0.16	0.25	0.26
23.00	1.00	1.00	1.00	2.00	92.60	24.30	80.00	2.50	10.00	77.60	0.16	0.25	0.26
23.00	1.00	1.00	1.00	2.00	92.60	24.30	80.00	4.00	9.00	75.20	0.16	0.25	0.26
23.00	1.00	1.00	2.00	3.00	92.60	24.30	80.00	2.50	11.00	78.40	0.16	0.25	0.26
23.00	1.00	1.00	2.00	3.00	92.60	24.30	80.00	4.00	10.00	77.60	0.16	0.25	0.26
24.00	1.00	1.00	1.00	2.00	101.70	74.30	80.00	2.50	32.00	83.20	0.16	0.25	0.26
24.00	1.00	1.00	1.00	2.00	101.70	74.30	80.00	4.00	33.00	81.60	0.16	0.25	0.26
24.00	1.00	1.00	2.00	3.00	101.70	74.30	80.00	2.50	31.00	88.80	0.16	0.25	0.26
24.00	1.00	1.00	2.00	3.00	101.70	74.30	80.00	4.00	34.00	84.00	0.16	0.25	0.26
25.00	2.00	1.00	1.00	2.00	101.40	56.10	10.00	2.50	3.00	56.80	0.15	0.21	0.22
25.00	2.00	1.00	1.00	2.00	101.40	56.10	10.00	4.00	4.00	69.60	0.15	0.21	0.22
25.00	2.00	1.00	2.00	3.00	101.90	59.20	40.00	2.50	16.00	81.60	0.15	0.21	0.22
25.00	2.00	1.00	2.00	3.00	101.90	59.20	40.00	4.00	18.00	71.20	0.15	0.21	0.22
26.00	2.00	1.00	1.00	2.00	102.00	59.80	10.00	2.50	5.00	69.60	0.15	0.21	0.22
26.00	2.00	1.00	1.00	2.00	102.00	59.80	10.00	4.00	6.00	65.60	0.15	0.21	0.22
26.00	2.00	1.00	2.00	3.00	102.50	62.80	40.00	2.50	17.00	76.00	0.15	0.21	0.22
26.00	2.00	1.00	2.00	3.00	102.50	62.80	40.00	4.00	21.00	65.60	0.15	0.21	0.22
27.00	3.00	1.00	1.00	2.00	106.10	19.20	10.00	2.50	3.00	72.00	0.47	2.10	2.50
27.00	3.00	1.00	1.00	2.00	106.10	19.20	10.00	4.00	2.00	76.00	0.47	2.10	2.50
27.00	3.00	1.00	2.00	3.00	107.00	24.20	40.00	2.50	7.00	69.30	0.47	2.10	2.50
27.00	3.00	1.00	2.00	3.00	107.00	24.20	40.00	4.00	8.00	68.00	0.47	2.10	2.50
27.00	3.00	1.00	3.00	4.00	108.60	32.90	80.00	2.50	11.00	68.00	0.47	2.10	2.50
27.00	3.00	1.00	3.00	4.00	108.60	32.90	80.00	4.00	12.00	68.00	0.47	2.10	2.50
28.00	3.00	1.00	1.00	2.00	112.80	53.70	10.00	2.50	11.00	80.00	0.47	2.10	2.50
28.00	3.00	1.00	1.00	2.00	112.80	53.70	10.00	4.00	12.00	81.30	0.47	2.10	2.50
28.00	3.00	1.00	2.00	3.00	113.10	56.20	40.00	2.50	22.00	78.00	0.47	2.10	2.50
28.00	3.00	1.00	2.00	3.00	113.10	56.20	40.00	4.00	26.00	90.70	0.47	2.10	2.50
28.00	3.00	1.00	3.00	4.00	113.50	58.10	80.00	2.50	33.00	79.30	0.47	2.10	2.50
28.00	3.00	1.00	3.00	4.00	113.50	58.10	80.00	4.00	35.00	90.00	0.47	2.10	2.50
29.00	3.00	1.00	4.00	5.00	120.70	91.40	10.00	2.50	53.00	98.70	0.47	2.10	2.50
29.00	3.00	1.00	4.00	5.00	120.70	91.40	10.00	4.00	52.00	88.70	0.47	2.10	2.50
29.00	3.00	1.00	1.00	2.00	120.70	91.40	10.00	2.50	47.00	80.00	0.47	2.10	2.50
29.00	3.00	1.00	1.00	2.00	120.70	91.40	10.00	4.00	46.00	80.00	0.47	2.10	2.50
29.00	3.00	1.00	2.00	3.00	120.70	91.40	40.00	2.50	73.00	86.00	0.47	2.10	2.50
29.00	3.00	1.00	2.00	3.00	120.70	91.40	40.00	4.00	66.00	85.30	0.47	2.10	2.50
29.00	3.00	1.00	3.00	4.00	120.70	91.40	80.00	2.50	94.00	92.00	0.47	2.10	2.50
29.00	3.00	1.00	3.00	4.00	120.70	91.40	80.00	4.00	78.00	88.00	0.47	2.10	2.50
30.00	4.00	1.00	1.00	2.00	104.70	20.10	10.00	2.50	2.00	69.30	0.28	0.50	0.60
30.00	4.00	1.00	1.00	2.00	104.70	20.10	10.00	4.00	1.00	68.70	0.28	0.50	0.60

(Continued)

Table 4 (Concluded)

30.00	4.00	1.00	2.00	3.00	107.60	25.90	40.00	2.50	9.00	75.30	0.28	0.50	0.60
30.00	4.00	1.00	2.00	3.00	107.60	25.90	40.00	4.00	8.00	72.70	0.28	0.50	0.60
30.00	4.00	1.00	3.00	4.00	108.20	29.70	80.00	2.50	16.00	81.30	0.28	0.50	0.60
30.00	4.00	1.00	3.00	4.00	108.20	29.70	80.00	4.00	17.00	80.70	0.28	0.50	0.60
31.00	4.00	1.00	4.00	1.00	119.80	95.90	10.00	2.50	38.00	94.00	0.28	0.50	0.60
31.00	4.00	1.00	4.00	1.00	119.80	95.90	10.00	4.00	38.00	90.00	0.28	0.50	0.60
31.00	4.00	1.00	1.00	2.00	119.80	95.90	10.00	2.50	30.00	88.00	0.28	0.50	0.60
31.00	4.00	1.00	1.00	2.00	119.80	95.90	10.00	4.00	39.00	90.70	0.28	0.50	0.60
31.00	4.00	1.00	2.00	3.00	119.80	95.90	40.00	2.50	60.00	88.70	0.28	0.50	0.60
31.00	4.00	1.00	2.00	3.00	119.80	95.90	40.00	4.00	74.00	94.70	0.28	0.50	0.60
31.00	4.00	1.00	3.00	4.00	119.80	95.90	80.00	2.50	78.00	93.30	0.28	0.50	0.60
31.00	4.00	1.00	3.00	4.00	119.80	95.90	80.00	4.00	86.00	100.00	0.28	0.50	0.60
32.00	4.00	1.00	1.00	2.00	111.40	49.30	10.00	2.50	9.00	78.00	0.28	0.50	0.60
32.00	4.00	1.00	1.00	2.00	111.40	49.30	10.00	4.00	9.00	74.70	0.28	0.50	0.60
32.00	4.00	1.00	2.00	3.00	111.60	50.50	40.00	2.50	20.00	74.00	0.28	0.50	0.60
32.00	4.00	1.00	2.00	3.00	111.60	50.50	40.00	4.00	23.00	78.00	0.28	0.50	0.60
32.00	4.00	1.00	3.00	4.00	111.80	51.70	80.00	2.50	35.00	79.30	0.28	0.50	0.60
32.00	4.00	1.00	3.00	4.00	111.80	51.70	80.00	4.00	37.00	79.30	0.28	0.50	0.60

Table 5

Selected Statistical Data Base for WES-Derived Data Developed by WES

TEST NO.	SAND TYPE	OCR	HOLE NO.	SEQUENCE	CORRECTED DRY DENSITY (PCF)	RELATIVE DENSITY (PERCENT)	VERTICAL STRESS (PSI)	DEPTH (FEET)	SPT N VALUE	RECOVERY (PERCENT)	D(10) MM	D(50) MM	D(60) MM
2.00	1.00	1.00	3.00	2.00	95.90	43.80	10.00	2.50	6.00	63.30	0.16	0.25	0.26
2.00	1.00	1.00	3.00	2.00	95.90	43.80	10.00	4.00	9.00	66.70	0.16	0.25	0.26
2.00	1.00	1.00	2.00	3.00	94.20	45.30	40.00	2.50	15.00	73.30	0.16	0.25	0.26
2.00	1.00	1.00	2.00	3.00	94.20	45.30	40.00	4.00	20.00	73.30	0.16	0.25	0.26
2.00	1.00	1.00	1.00	4.00	94.30	46.10	80.00	2.50	25.00	66.70	0.16	0.25	0.26
2.00	1.00	1.00	1.00	4.00	94.30	46.10	80.00	4.00	31.00	66.70	0.16	0.25	0.26
4.00	1.00	1.00	2.00	2.00	92.60	24.30	10.00	2.50	3.00	1.00	0.16	0.25	0.26
4.00	1.00	1.00	2.00	2.00	92.60	24.30	10.00	4.00	3.00	1.00	0.16	0.25	0.26
4.00	1.00	1.00	1.00	3.00	93.20	27.80	40.00	2.50	6.00	1.00	0.16	0.25	0.26
4.00	1.00	1.00	1.00	3.00	93.20	27.80	40.00	4.00	9.00	1.00	0.16	0.25	0.26
4.00	1.00	1.00	3.00	4.00	93.40	29.50	80.00	2.50	14.00	1.00	0.16	0.25	0.26
4.00	1.00	1.00	3.00	4.00	93.40	29.50	80.00	4.00	16.00	1.00	0.16	0.25	0.26
5.00	1.00	1.00	2.00	2.00	98.70	59.00	10.00	2.50	13.00	1.00	0.16	0.25	0.26
5.00	1.00	1.00	2.00	2.00	98.70	59.00	10.00	4.00	11.00	1.00	0.16	0.25	0.26
5.00	1.00	1.00	3.00	3.00	98.80	59.70	40.00	2.50	23.00	1.00	0.16	0.25	0.26
5.00	1.00	1.00	3.00	3.00	98.80	59.70	40.00	4.00	22.00	1.00	0.16	0.25	0.26
6.00	1.00	3.00	2.00	2.00	98.20	56.30	10.00	2.50	12.00	1.00	0.16	0.25	0.26
6.00	1.00	3.00	2.00	2.00	98.20	56.30	10.00	4.00	12.00	1.00	0.16	0.25	0.26
6.00	1.00	3.00	3.00	3.00	98.40	57.30	40.00	2.50	25.00	84.00	0.16	0.25	0.26
6.00	1.00	3.00	3.00	3.00	98.40	57.30	40.00	4.00	27.00	88.00	0.16	0.25	0.26
6.00	1.00	3.00	1.00	4.00	98.70	59.00	80.00	2.50	35.00	88.00	0.16	0.25	0.26
6.00	1.00	3.00	1.00	4.00	98.70	59.00	80.00	4.00	38.00	88.00	0.16	0.25	0.26
7.00	1.00	3.00	1.00	2.00	94.90	38.00	10.00	2.50	5.00	88.00	0.16	0.25	0.26
7.00	1.00	3.00	1.00	2.00	94.90	38.00	10.00	4.00	4.00	84.00	0.16	0.25	0.26
7.00	1.00	3.00	2.00	3.00	95.20	39.70	40.00	2.50	16.00	92.00	0.16	0.25	0.26
7.00	1.00	3.00	2.00	3.00	95.20	39.70	40.00	4.00	16.00	84.00	0.16	0.25	0.26
7.00	1.00	3.00	3.00	4.00	95.40	40.90	80.00	2.50	27.00	92.00	0.16	0.25	0.26
7.00	1.00	3.00	3.00	4.00	95.40	40.90	80.00	4.00	30.00	88.00	0.16	0.25	0.26
8.00	1.00	1.00	4.00	1.00	94.30	45.70	40.00	2.50	9.00	1.00	0.16	0.25	0.26
8.00	1.00	1.00	4.00	1.00	94.30	45.70	40.00	4.00	13.00	1.00	0.16	0.25	0.26
8.00	1.00	1.00	1.00	2.00	94.30	45.70	40.00	2.50	12.00	1.00	0.16	0.25	0.26
8.00	1.00	1.00	1.00	2.00	94.30	45.70	40.00	4.00	13.00	1.00	0.16	0.25	0.26
8.00	1.00	1.00	2.00	3.00	94.30	45.70	40.00	2.50	12.00	1.00	0.16	0.25	0.26
8.00	1.00	1.00	2.00	3.00	94.30	45.70	40.00	4.00	13.00	1.00	0.16	0.25	0.26
8.00	1.00	1.00	3.00	4.00	94.30	45.70	40.00	2.50	14.00	1.00	0.16	0.25	0.26
8.00	1.00	1.00	3.00	4.00	94.30	45.70	40.00	4.00	17.00	1.00	0.16	0.25	0.26
11.00	1.00	1.00	4.00	1.00	94.40	35.10	40.00	2.50	5.00	92.00	0.16	0.25	0.26

(Continued)

(Sheet 1 of 4)

Table 5 (Continued)

11.00	1.00	1.00	4.00	1.00	94.40	35.10	40.00	4.00	7.00	88.00	0.16	0.25	0.26
11.00	1.00	1.00	1.00	2.00	94.40	35.10	40.00	2.50	7.00	88.00	0.16	0.25	0.26
11.00	1.00	1.00	1.00	2.00	94.40	35.10	40.00	4.00	9.00	89.20	0.16	0.25	0.26
11.00	1.00	1.00	2.00	3.00	94.40	35.10	40.00	2.50	8.00	90.40	0.16	0.25	0.26
11.00	1.00	1.00	2.00	3.00	94.40	35.10	40.00	4.00	8.00	90.40	0.16	0.25	0.26
12.00	1.00	1.00	1.00	2.00	101.10	71.50	40.00	2.50	27.00	72.00	0.16	0.25	0.26
12.00	1.00	1.00	4.00	1.00	101.10	71.50	40.00	2.50	35.00	84.00	0.16	0.25	0.26
12.00	1.00	1.00	4.00	1.00	101.10	71.50	40.00	4.00	32.00	72.00	0.16	0.25	0.26
12.00	1.00	1.00	1.00	2.00	101.10	71.50	40.00	4.00	31.00	72.00	0.16	0.25	0.26
12.00	1.00	1.00	2.00	3.00	101.10	71.50	40.00	2.50	30.00	76.00	0.16	0.25	0.26
12.00	1.00	1.00	2.00	3.00	101.10	71.50	40.00	4.00	32.00	80.00	0.16	0.25	0.26
13.00	1.00	1.00	1.00	2.00	96.70	48.20	40.00	2.50	9.00	72.00	0.16	0.25	0.26
13.00	1.00	1.00	4.00	1.00	96.70	48.20	40.00	2.50	8.00	76.00	0.16	0.25	0.26
13.00	1.00	1.00	4.00	1.00	96.70	48.20	40.00	4.00	8.00	70.40	0.16	0.25	0.26
13.00	1.00	1.00	1.00	2.00	96.70	48.20	40.00	4.00	9.00	72.00	0.16	0.25	0.26
13.00	1.00	1.00	2.00	3.00	96.70	48.20	40.00	2.50	12.00	74.40	0.16	0.25	0.26
13.00	1.00	1.00	2.00	3.00	96.70	48.20	40.00	4.00	11.00	68.00	0.16	0.25	0.26
16.00	1.00	1.00	4.00	1.00	93.00	27.10	10.00	4.00	1.00	60.00	0.16	0.25	0.26
16.00	1.00	1.00	4.00	1.00	93.00	27.10	10.00	2.50	1.00	60.00	0.16	0.25	0.26
16.00	1.00	1.00	1.00	2.00	93.00	27.10	10.00	2.50	1.00	52.00	0.16	0.25	0.26
16.00	1.00	1.00	1.00	2.00	93.00	27.10	10.00	4.00	1.00	48.00	0.16	0.25	0.26
17.00	1.00	1.00	4.00	1.00	101.50	73.20	10.00	2.50	17.00	78.40	0.16	0.25	0.26
17.00	1.00	1.00	4.00	1.00	101.50	73.20	10.00	4.00	24.00	68.80	0.16	0.25	0.26
17.00	1.00	1.00	1.00	2.00	101.50	73.20	10.00	2.50	15.00	72.00	0.16	0.25	0.26
17.00	1.00	1.00	1.00	2.00	101.50	73.20	10.00	4.00	19.00	70.40	0.16	0.25	0.26
17.00	1.00	1.00	2.00	3.00	101.50	73.20	10.00	2.50	15.00	75.20	0.16	0.25	0.26
17.00	1.00	1.00	2.00	3.00	101.50	73.20	10.00	4.00	19.00	68.80	0.16	0.25	0.26
18.00	1.00	1.00	4.00	1.00	101.70	74.40	80.00	2.50	33.00	67.20	0.16	0.25	0.26
18.00	1.00	1.00	4.00	1.00	101.70	74.40	80.00	4.00	42.00	72.80	0.16	0.25	0.26
18.00	1.00	1.00	1.00	2.00	101.70	74.40	80.00	2.50	38.00	80.80	0.16	0.25	0.24
18.00	1.00	1.00	1.00	2.00	101.70	74.40	80.00	4.00	45.00	70.20	0.16	0.25	0.26
18.00	1.00	1.00	2.00	3.00	101.70	74.40	80.00	2.50	46.00	76.80	0.16	0.25	0.26
18.00	1.00	1.00	2.00	3.00	101.70	74.40	80.00	4.00	49.00	83.20	0.16	0.25	0.26
19.00	1.00	1.00	4.00	1.00	101.50	73.50	40.00	2.50	20.00	78.40	8.16	0.25	0.26
19.00	1.00	1.00	4.00	1.00	101.50	73.50	40.00	4.00	23.00	80.00	0.16	0.25	0.26
19.00	1.00	1.00	1.00	2.00	101.50	73.50	40.00	2.50	27.00	75.20	0.16	0.25	0.26
19.00	1.00	1.00	1.00	2.00	101.50	73.50	40.00	4.00	24.00	76.00	0.16	0.25	0.26
19.00	1.00	1.00	2.00	3.00	101.50	73.50	40.00	2.50	26.00	68.80	0.16	0.25	0.26
19.00	1.00	1.00	2.00	3.00	101.50	73.50	40.00	4.00	26.00	70.40	0.16	0.25	0.26
20.00	1.00	1.00	4.00	1.00	96.20	45.30	40.00	2.50	8.00	78.40	0.16	0.25	0.26
20.00	1.00	1.00	4.00	1.00	96.20	45.30	40.00	4.00	9.00	79.20	0.16	0.25	0.26
20.00	1.00	1.00	1.00	2.00	96.20	45.30	40.00	2.50	13.00	71.20	0.16	0.25	0.26
20.00	1.00	1.00	1.00	2.00	96.20	45.30	40.00	4.00	10.00	65.60	0.16	0.25	0.26

(Continued)

Table 5 (Continued)

20.00	1.00	1.00	3.00	3.00	96.20	45.30	40.00	2.50	12.00	74.40	0.16	0.25	0.26
20.00	1.00	1.00	3.00	3.00	96.20	45.30	40.00	4.00	15.00	67.20	0.16	0.25	0.26
20.00	1.00	1.00	2.00	4.00	96.20	45.30	40.00	2.50	13.00	69.60	0.16	0.25	0.26
20.00	1.00	1.00	2.00	4.00	96.20	45.30	40.00	4.00	12.00	66.40	0.16	0.25	0.26
21.00	1.00	1.00	4.00	1.00	94.80	37.60	40.00	2.50	8.00	76.80	0.16	0.25	0.26
21.00	1.00	1.00	4.00	1.00	94.80	37.60	40.00	4.00	11.00	80.80	0.16	0.25	0.26
21.00	1.00	1.00	1.00	2.00	94.80	37.60	40.00	2.50	8.00	72.80	0.16	0.25	0.26
21.00	1.00	1.00	1.00	2.00	94.80	37.60	40.00	4.00	9.00	66.40	0.16	0.25	0.26
21.00	1.00	1.00	2.00	3.00	94.80	37.60	40.00	2.50	9.00	72.80	0.16	0.25	0.26
21.00	1.00	1.00	2.00	3.00	94.80	37.60	40.00	4.00	11.00	1.00	0.16	0.25	0.26
22.00	1.00	1.00	1.00	2.00	93.70	53.80	80.00	2.50	20.00	79.20	0.16	0.25	0.26
22.00	1.00	1.00	1.00	2.00	93.70	53.80	80.00	4.00	22.00	71.20	0.16	0.25	0.26
22.00	1.00	1.00	2.00	3.00	93.70	53.80	80.00	2.50	20.00	72.80	0.16	0.25	0.26
22.00	1.00	1.00	2.00	3.00	93.70	53.80	80.00	4.00	20.00	70.40	0.16	0.25	0.26
23.00	1.00	1.00	1.00	2.00	92.60	24.30	80.00	2.50	10.00	77.60	0.16	0.25	0.26
23.00	1.00	1.00	1.00	2.00	92.60	24.30	80.00	4.00	9.00	75.20	0.16	0.25	0.26
23.00	1.00	1.00	2.00	3.00	92.60	24.30	80.00	2.50	11.00	78.40	0.16	0.25	0.24
23.00	1.00	1.00	2.00	3.00	92.60	24.30	80.00	4.00	10.00	79.60	0.16	0.25	0.26
24.00	1.00	1.00	1.00	2.00	101.70	74.30	80.00	2.50	32.00	83.20	0.16	0.25	0.26
24.00	1.00	1.00	1.00	2.00	101.70	74.30	80.00	4.00	33.00	81.60	0.16	0.25	0.26
24.00	1.00	1.00	2.00	3.00	101.70	74.30	80.00	2.50	31.00	88.80	0.16	0.25	0.26
24.00	1.00	1.00	2.00	3.00	101.70	74.30	80.00	4.00	34.00	84.00	0.16	0.25	0.26
25.00	2.00	1.00	1.00	2.00	101.40	56.10	10.00	2.50	3.00	56.80	0.15	0.21	0.22
25.00	2.00	1.00	1.00	2.00	101.40	56.10	10.00	4.00	4.00	69.60	0.15	0.21	0.22
25.00	2.00	1.00	2.00	3.00	101.90	59.20	40.00	4.00	18.00	71.20	0.15	0.21	0.22
25.00	2.00	1.00	2.00	3.00	101.90	59.20	40.00	2.50	16.00	81.60	0.15	0.21	0.22
26.00	2.00	1.00	1.00	2.00	102.00	59.80	10.00	2.50	5.00	69.60	0.15	0.21	0.22
26.00	2.00	1.00	1.00	2.00	102.00	59.80	10.00	4.00	6.00	69.60	0.15	0.21	0.22
26.00	2.00	1.00	2.00	3.00	102.50	62.80	40.00	2.50	17.00	76.00	0.15	0.21	0.22
26.00	2.00	1.00	2.00	3.00	102.50	62.80	40.00	4.00	21.00	65.60	0.15	0.21	0.22
27.00	3.00	1.00	1.00	2.00	104.10	19.20	10.00	2.50	3.00	72.00	0.47	2.10	2.50
27.00	3.00	1.00	1.00	2.00	104.10	19.20	10.00	4.00	2.00	76.00	0.47	2.10	2.50
27.00	3.00	1.00	2.00	3.00	107.00	24.20	40.00	2.50	7.00	65.30	0.47	2.10	2.50
27.00	3.00	1.00	2.00	3.00	107.00	24.20	40.00	4.00	8.00	68.00	0.47	2.10	2.50
27.00	3.00	1.00	3.00	4.00	108.60	32.90	80.00	2.50	11.00	68.00	0.47	2.10	2.50
27.00	3.00	1.00	3.00	4.00	108.60	32.90	80.00	4.00	12.00	68.00	0.47	2.10	2.50
28.00	3.00	1.00	1.00	2.00	112.80	53.70	10.00	2.50	11.00	80.00	0.47	2.10	2.50
28.00	3.00	1.00	1.00	2.00	112.80	53.70	10.00	4.00	12.00	81.30	0.47	2.10	2.50
28.00	3.00	1.00	2.00	3.00	113.10	56.20	40.00	2.50	22.00	78.00	0.47	2.10	2.50
28.00	3.00	1.00	2.00	3.00	113.10	56.20	40.00	4.00	26.00	90.70	0.47	2.10	2.50
28.00	3.00	1.00	3.00	4.00	113.50	58.10	80.00	2.50	33.00	79.30	0.47	2.10	2.50
28.00	3.00	1.00	3.00	4.00	113.50	58.10	80.00	4.00	35.00	90.00	0.47	2.10	2.50
29.00	3.00	1.00	4.00	1.00	120.70	91.40	10.00	2.50	53.00	98.70	0.47	2.10	2.50

(Continued)

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Table 5 (Concluded)

29.00	3.00	1.00	4.00	1.00	120.70	91.40	10.00	4.00	52.00	88.70	0.47	2.10	2.50
29.00	3.00	1.00	1.00	2.00	120.70	91.40	10.00	2.50	47.00	80.00	0.47	2.10	2.50
29.00	3.00	1.00	1.00	2.00	120.70	91.40	10.00	4.00	46.00	80.00	0.47	2.10	2.50
29.00	3.00	1.00	2.00	3.00	120.70	91.40	40.00	2.50	73.00	86.00	0.47	2.10	2.50
29.00	3.00	1.00	2.00	3.00	120.70	91.40	40.00	4.00	66.00	85.30	0.47	2.10	2.50
29.00	3.00	1.00	3.00	4.00	120.70	91.40	80.00	2.50	94.00	92.00	0.47	2.10	2.50
29.00	3.00	1.00	3.00	4.00	120.70	91.40	80.00	4.00	78.00	88.00	0.47	2.10	2.50
30.00	4.00	1.00	1.00	2.00	104.70	20.10	10.00	2.50	2.00	69.30	0.28	0.50	0.60
30.00	4.00	1.00	1.00	2.00	104.70	20.10	10.00	4.00	1.00	68.70	0.28	0.50	0.60
30.00	4.00	1.00	2.00	3.00	107.60	25.90	40.00	2.50	9.00	75.30	0.28	0.50	0.60
30.00	4.00	1.00	2.00	3.00	107.60	25.90	40.00	4.00	8.00	72.70	0.28	0.50	0.60
30.00	4.00	1.00	3.00	4.00	108.20	29.70	80.00	2.50	16.00	81.30	0.28	0.50	0.60
30.00	4.00	1.00	3.00	4.00	108.20	29.70	80.00	4.00	17.00	80.70	0.28	0.50	0.60
31.00	4.00	1.00	4.00	1.00	119.80	95.90	10.00	2.50	38.00	94.00	0.28	0.50	0.60
31.00	4.00	1.00	4.00	1.00	119.80	95.90	10.00	4.00	38.00	90.00	0.28	0.50	0.60
31.00	4.00	1.00	1.00	2.00	119.80	95.90	10.00	2.50	30.00	88.00	0.28	0.50	0.60
31.00	4.00	1.00	1.00	2.00	119.80	95.90	10.00	4.00	39.00	90.70	0.28	0.50	0.60
31.00	4.00	1.00	2.00	3.00	119.80	95.90	40.00	2.50	60.00	88.70	0.28	0.50	0.60
31.00	4.00	1.00	2.00	3.00	119.80	95.90	40.00	4.00	74.00	94.70	0.28	0.50	0.60
31.00	4.00	1.00	3.00	4.00	119.80	95.90	80.00	2.50	78.00	93.30	0.28	0.50	0.60
31.00	4.00	1.00	3.00	4.00	119.80	95.90	80.00	4.00	86.00	100.00	0.28	0.50	0.60
32.00	4.00	1.00	1.00	2.00	111.40	49.30	10.00	2.50	9.00	78.00	0.28	0.50	0.60
32.00	4.00	1.00	1.00	2.00	111.40	49.30	10.00	4.00	9.00	74.70	0.28	0.50	0.60
32.00	4.00	1.00	2.00	3.00	111.60	50.50	40.00	2.50	20.00	76.00	0.28	0.50	0.60
32.00	4.00	1.00	3.00	4.00	111.80	51.70	80.00	2.50	35.00	79.30	0.28	0.50	0.60
32.00	4.00	1.00	2.00	3.00	111.60	50.50	40.00	4.00	23.00	78.00	0.28	0.50	0.60
-32.00	4.00	1.00	3.00	4.00	111.80	51.70	80.00	4.00	37.00	79.30	0.28	0.50	0.60

(Sheet 4 of 4)

Table 6

Coefficients for Expression

$$D_R = b_o + b_1 \left[\left| 222(N) + 2311 - 711(OCR) - 53(\bar{\sigma}_v) - 50(C_u)^2 \right| \right]^{1/2}$$

Sand	r^2	σ	b_o	b_1	No. of Data Points Analyzed
Reid Bedford Model sand (normally consolidated)	0.81	7.4	8.2	0.84	90
Ottawa sand *	--	--	--	--	8
Platte River sand	0.96	6.2	13.6	0.70	20
Standard Concrete sand	0.90	10.2	0	0.85	20
All data	0.85	8.1	12.2	0.75	150
All normally consolidated data	0.85	8.3	11.7	0.76	138

* A separate regression analysis is not reported for Ottawa sand because of the limited data.

Table 7

Comparison of Predicted and Laboratory Relative Densities

for All Normally Consolidated Data

$$D_R = 11.7 + 0.76\left[\left|222(N) + 1600 - 53(\bar{\sigma}_v) - 50(c_u)^2\right|\right]^{1/2}$$

$$\sigma = \pm 8.3\% \ , \quad r^2 = 0.85$$

SET	EXPECTED	OBSERVED	DIFFERENCE
1	47.81595468	43.80000019	4.01595461
2	52.77396584	43.80000019	8.97396564
~~3~~	~~50.92772007~~	~~45.30000019~~	~~5.62772030~~
4	58.35472679	45.30000019	13.05472684
5	51.65344572	46.09999990	5.55344593
~~6~~	~~60.29730320~~	~~46.09999990~~	~~14.19730330~~
7	42.05878210	24.29999995	17.75878215
8	42.05878210	24.29999995	17.75878215
~~9~~	~~31.46612620~~	~~27.79999995~~	~~3.66612628~~
10	39.51008320	27.79999995	11.71008337
11	25.59361482	29.50000000	-3.90638512
~~12~~	~~32.86983394~~	~~29.50000000~~	~~3.36983424~~
13	58.57590628	59.00000000	-0.42409347
14	55.77051592	59.00000000	-3.22948367
~~15~~	~~62.29026079~~	~~59.69999981~~	~~2.59026128~~
16	61.01332569	59.69999981	1.31332611
17	39.51008320	45.69999981	-6.18991649
~~18~~	~~47.52841425~~	~~45.69999981~~	~~1.82841481~~
19	45.70156193	45.69999981	0.00156227
20	47.52841425	45.69999981	1.82841481
~~21~~	~~45.70156193~~	~~45.69999981~~	~~0.00156227~~
22	47.52841425	45.69999981	1.82841481
23	49.26653528	45.69999981	3.56653556
~~24~~	~~54.05508757~~	~~45.69999981~~	~~8.35508811~~
25	27.92143155	35.09999990	-7.17856824
26	34.46545553	35.09999990	-0.63454425
~~27~~	~~34.46545553~~	~~35.09999990~~	~~-0.63454425~~
28	39.51008320	35.09999990	4.41008341
29	37.11324549	35.09999990	2.01324564
~~30~~	~~37.11324549~~	~~35.09999990~~	~~2.01324564~~
31	75.65485954	71.50000000	4.15486020
32	72.58933449	71.50000000	1.08933462
~~33~~	~~67.10448360~~	~~71.50000000~~	~~-4.39551598~~
34	71.53260040	71.50000000	0.03260090
35	70.45686531	71.50000000	-1.04313457
~~36~~	~~72.58933449~~	~~71.50000000~~	~~1.08933462~~
37	37.11324549	48.19999981	-11.08675432
38	37.11324549	48.19999981	-11.08675432
39	39.51008320	48.19999981	-8.68991649
~~40~~	~~39.51008320~~	~~48.19999981~~	~~-8.68991649~~
41	45.70156193	48.19999981	-2.49843773
42	43.77081824	48.19999981	-4.42918128

Reid Bedford Model sand

Table 7 (Continued)

Reid Bedford Model sand

SET	EXPECTED	OBSERVED	DIFFERENCE
43	37.51704168	27.09999990	10.41704214
44	37.51704168	27.09999990	10.41704214
45	37.51704168	27.09999990	10.41704214
46	37.51704168	27.09999990	10.41704214
47	63.73491240	73.19999981	-9.46508741
48	71.70522690	73.19999981	-1.49477248
49	61.22263288	73.19999981	-11.97736669
50	66.13136292	73.19999981	-7.06863654
51	61.22263288	73.19999981	-11.97736669
52	66.13136292	73.19999981	-7.06863654
53	62.85504532	74.39999962	-11.54495406
54	73.05939579	74.39999962	-1.34060365
55	69.85722351	74.39999962	-4.54277545
56	76.10255051	74.39999962	1.70255150
57	77.08547020	74.39999962	2.68547054
58	79.94934560	74.39999962	5.54934680
59	58.35472679	73.50000000	-15.14527297
60	62.29026079	73.50000000	-11.20973897
61	67.10448360	73.50000000	-6.39551598
62	63.53574992	73.50000000	-9.96424985
63	65.94099998	73.50000000	-7.55899918
64	65.94099998	73.50000000	-7.55899918
65	37.11324549	45.30000019	-8.18675470
66	39.51008320	45.30000019	-5.78991687
67	47.52841425	45.30000019	2.22841442
68	41.71614361	45.30000019	-3.58385644
69	45.70156193	45.30000019	0.40156189
70	50.92772087	45.30000019	5.62772030
71	47.52841425	45.30000019	2.22841442
72	45.70156193	45.30000019	0.40156189
73	37.11324549	37.59999991	-0.48675436
74	43.77081824	37.59999991	6.17081863
75	37.11324549	37.59999991	-0.48675436
76	39.51008320	37.59999991	1.91008344
77	39.51008320	37.59999991	1.91008344
78	43.77081824	37.59999991	6.17081863
79	42.65855503	53.80000019	-11.14144504
80	46.53632784	53.80000019	-7.26367235
81	42.65855503	53.80000019	-11.14144504
82	42.65855503	53.80000019	-11.14144504
83	29.50967479	24.29999995	5.20967489
84	32.78909779	24.29999995	8.48909819
85	25.47028732	24.29999995	1.17028759
86	29.50967479	24.29999995	5.20967489
87	61.59256696	74.30000019	-12.70743322
88	62.85504532	74.30000019	-11.44495463
89	60.29730320	74.30000019	-14.00269699
90	64.08710861	74.30000019	-10.21289110
91	42.28954363	56.09999990	-13.81045628
92	44.30810881	56.09999990	-11.79189074

Table 7 (Concluded)

SET		EXPECTED	OBSERVED	DIFFERENCE
93	Ottawa sand	55.67531870	59.19999981	-3.50469087
94		52.69327212	59.19999981	-6.50672764
95		46.20880556	59.80000019	-13.59119439
96		48.01014709	59.80000019	-11.78985274
97		54.22079658	62.80000019	-8.57920337
98		59.84871244	62.80000019	-2.95128760
99	Platte River sand	25.28759003	19.20000005	6.08759004
100		19.25405502	19.20000005	0.05405500
101		26.48907065	24.20000005	2.28907067
102		21.24755621	24.20000005	-2.95244372
103		42.14099360	32.90000010	9.24099374
104		39.96810675	32.90000010	7.06810695
105		46.41540480	53.69999981	-7.28459460
106		48.20655441	53.69999981	-5.49344534
107		52.86734295	56.19999981	-3.33265686
108		58.65774775	56.19999981	2.45774814
109		55.05647421	58.09999990	-3.04352564
110		57.90523719	58.09999990	-0.19476255
111		92.71317291	91.39999962	1.31317353
112		91.92195797	91.39999962	0.52195896
113		87.84266186	91.39999962	-3.55733740
114		87.00028896	91.39999962	-4.39971048
115		102.25870419	91.39999962	10.85870528
116		97.18612003	91.39999962	5.78612089
117		109.99361230	91.39999962	18.59361338
118		98.99538899	91.39999962	7.59538954
119	Standard Concrete sand	38.86663676	20.09999990	18.76663709
120		36.40746117	20.09999990	16.30746126
121		38.48319435	25.90000010	12.58319438
122		35.98522282	25.90000010	10.08522308
123		31.50155234	29.70000005	1.80155252
124		34.49622154	29.70000005	4.79622156
125		84.71069145	95.89999962	-11.18930805
126		84.71069145	95.89999962	-11.18930805
127		77.35052109	95.89999962	-18.54947853
128		85.57917500	95.89999962	-10.32082462
129		96.69086361	95.89999962	0.79086467
130		106.61813259	95.89999962	10.71813345
131		102.81248951	95.89999962	6.91248989
132		108.25081825	95.89999962	12.35081899
133		52.08574772	49.30000019	2.78574759
134		52.08574772	49.30000019	2.78574759
135		57.74998665	50.50000000	7.24998695
136		61.73311043	50.50000000	11.23311055
137		64.76521778	51.69999981	13.06521797
138		67.11713314	51.69999981	15.41713333

Table 8

Comparison of Predicted and Laboratory Relative Densities for Normally Consolidated Reid Bedford Model Sand

$$D_R = 8.2 + 0.84\left[\left|222(N) + 1600 - 53(\bar{\sigma}_v) - 50(C_u)^2\right|\right]^{1/2}$$

$$r^2 = 0.81\ ,\quad \sigma = \underline{+}7.4\%$$

SET	EXPECTED	OBSERVED	DIFFERENCE
1	48.26295996	43.80000019	4.46295983
2	53.76752138	43.80000019	9.96752154
3	51.71775389	45.30000019	6.41775370
4	59.96348286	45.30000019	14.66348279
5	52.52347994	46.09999990	6.42348033
6	62.12020063	46.09999990	16.02020097
7	41.87114000	24.29999995	17.57114029
8	41.87114000	24.29999995	17.57114029
9	30.11079359	27.79999995	2.31079385
10	39.04148340	27.79999995	11.24148357
11	23.59092092	29.50000000	-5.90907901
12	31.66924071	29.50000000	2.16924077
13	60.20904398	59.00000000	1.20904444
14	57.09439945	59.00000000	-1.90560038
15	64.33285332	59.69999981	4.63285428
16	62.91515445	59.69999981	3.21515506
17	39.04148340	45.69999981	-6.65851629
18	47.94372225	45.69999981	2.24372280
19	45.91548491	45.69999981	0.21548556
20	47.94372225	45.69999981	2.24372280
21	45.91548491	45.69999981	0.21548556
22	47.94372225	45.69999981	2.24372280
23	49.87344646	45.69999981	4.17344677
24	55.18986940	45.69999981	9.48986960
25	26.17534661	35.09999990	-8.92465317
26	33.44075680	35.09999990	-1.65924299
27	33.44075680	35.09999990	-1.65924299
28	39.04148340	35.09999990	3.94148364
29	36.38042784	35.09999990	1.28042833
30	36.38042784	35.09999990	1.28042833
31	79.17071152	71.50000000	7.67071152
32	75.76725483	71.50000000	4.26725501
33	69.67777633	71.50000000	-1.82222281
34	74.59403134	71.50000000	3.09403133
35	73.39971065	71.50000000	1.89971124
36	75.76725483	71.50000000	4.26725501
37	36.38042784	48.19999981	-11.81957162

Table 8 (Concluded)

SET	EXPECTED	OBSERVED	DIFFERENCE
38	36.38042784	48.19999981	-11.81957162
39	39.04148340	48.19999981	-9.15851629
40	39.04148340	48.19999981	-9.15851629
41	45.91548491	48.19999981	-2.28451446
42	43.77190447	48.19999981	-4.42809516
43	36.82873726	27.09999990	9.72873771
44	36.82873726	27.09999990	9.72873771
45	36.82873726	27.09999990	9.72873771
46	36.82873726	27.09999990	9.72873771
47	65.93675709	73.19999981	-7.26324195
48	74.78568649	73.19999981	1.58568759
49	63.14753532	73.19999981	-10.05246449
50	68.59738350	73.19999981	-4.60261625
51	63.14753532	73.19999981	-10.05246449
52	68.59738350	73.19999981	-4.60261625
53	64.95989799	74.39999962	-9.44010151
54	76.28913307	74.39999962	1.88913440
55	72.73396778	74.39999962	-1.66603157
56	79.66775322	74.39999962	5.26775449
57	80.75902558	74.39999962	6.35902649
58	83.93860340	74.39999962	9.53860450
59	59.96348286	73.50000000	-13.53651703
60	64.33285332	73.50000000	-9.16714597
61	69.67777633	73.50000000	-3.82222283
62	65.71564007	73.50000000	-7.78435916
63	68.38603592	73.50000000	-5.11396366
64	68.38603592	73.50000000	-5.11396366
65	36.38042784	45.30000019	-8.91957200
66	39.04148340	45.30000019	-6.25851667
67	47.94372225	45.30000019	2.64372241
68	41.49073076	45.30000019	-3.80926922
69	45.91548491	45.30000019	0.61548517
70	51.71775389	45.30000019	6.41775370
71	47.94372225	45.30000019	2.64372241
72	45.91548491	45.30000019	0.61548517
73	36.38042784	37.59999991	-1.21957167
74	43.77190447	37.59999991	6.17190474
75	36.38042784	37.59999991	-1.21957167
76	39.04148340	37.59999991	1.44148366
77	39.04148340	37.59999991	1.44148366
78	43.77190447	37.59999991	6.17190474
79	42.53702974	53.80000019	-11.26297021
80	46.84227228	53.80000019	-6.95772791
81	42.53702974	53.80000019	-11.26297021
82	42.53702974	53.80000019	-11.26297021
83	27.93867111	24.29999995	3.63867134
84	31.57960463	24.29999995	7.27960473
85	23.45399857	24.29999995	-0.84600137
86	27.93867111	24.29999995	3.63867134
87	63.55824900	74.30000019	-10.74175107
88	64.95989799	74.30000019	-9.34010208
89	62.12020063	74.30000019	-12.17979932
90	66.32777882	74.30000019	-7.97222090

Table 9

Comparison of Predicted and Laboratory Relative Densities

for Platte River Sand

$$D_R = 13.6 + 0.7\left[\left|222(N) + 1600 - 53(\bar{\sigma}_v) - 50(C_u)^2\right|\right]^{1/2}$$

$$r^2 = 0.96\ ,\quad \sigma = \pm 6.2\%$$

SET	EXPECTED	OBSERVED	DIFFERENCE
1	26,12958717	19.20000005	6.92958731
2	20,56273008	19.20000005	1.36273010
3	27,23813653	24.20000005	3.03813663
4	22,40203929	24.20000005	-1.79796061
5	41,67942524	32.90000010	8.77942515
6	39,67460537	32.90000010	6.77460540
7	45,62322235	53.69999981	-8.07677746
8	47,27583075	53.69999981	-6.42416888
9	51,57611990	56.19999981	-4.62387991
10	56,91865205	56.19999981	0.71865271
11	53,59592771	58.09999990	-4.50407219
12	56,22434616	58.09999990	-1.87565333
13	88,33998108	91.39999962	-3.06001824
14	87,60996437	91.39999962	-3.79003447
15	83,84619141	91.39999962	-7.55380816
16	83,06897354	91.39999962	-8.33102596
17	97,14719105	91.39999962	5.74719208
18	92,46695804	91.39999962	1.06695859
19	104,28382492	91.39999962	12.88382566
20	94,13628388	91.39999962	2.73628512

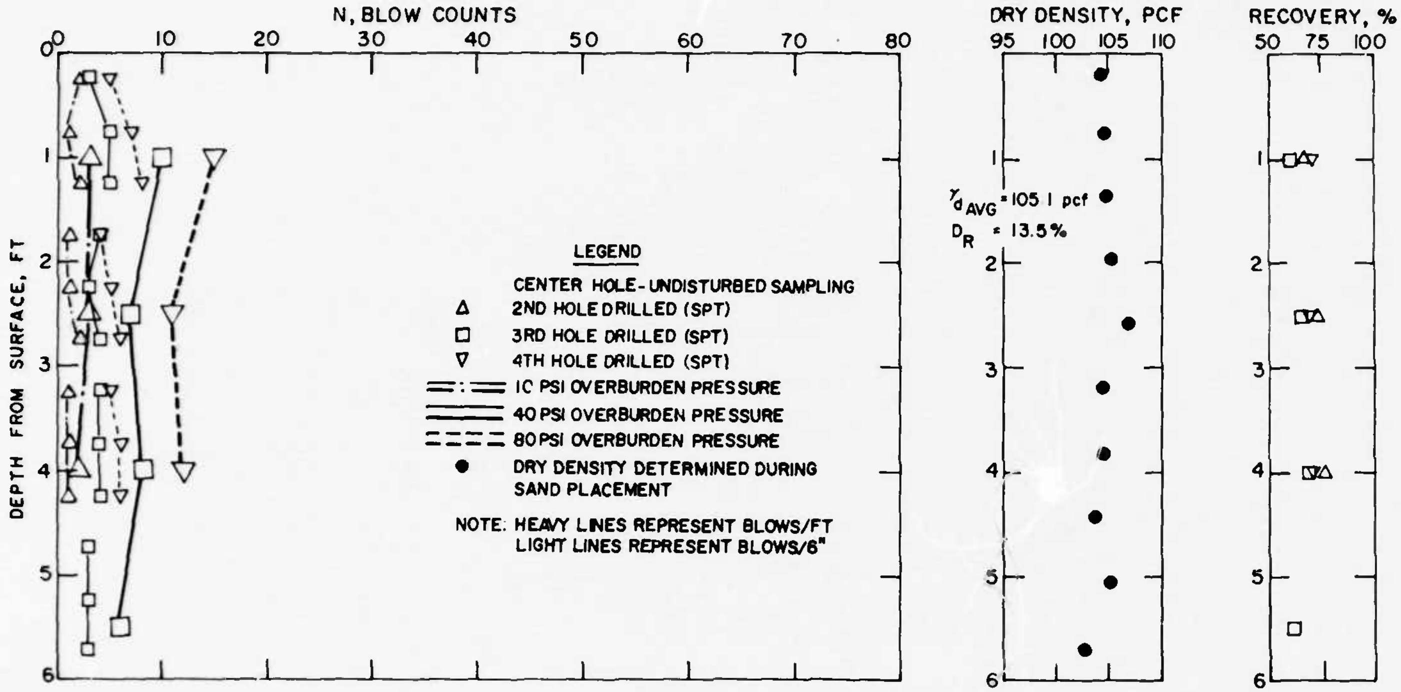
Table 10

Comparison of Predicted and Laboratory Relative Densities
for Standard Concrete Sand

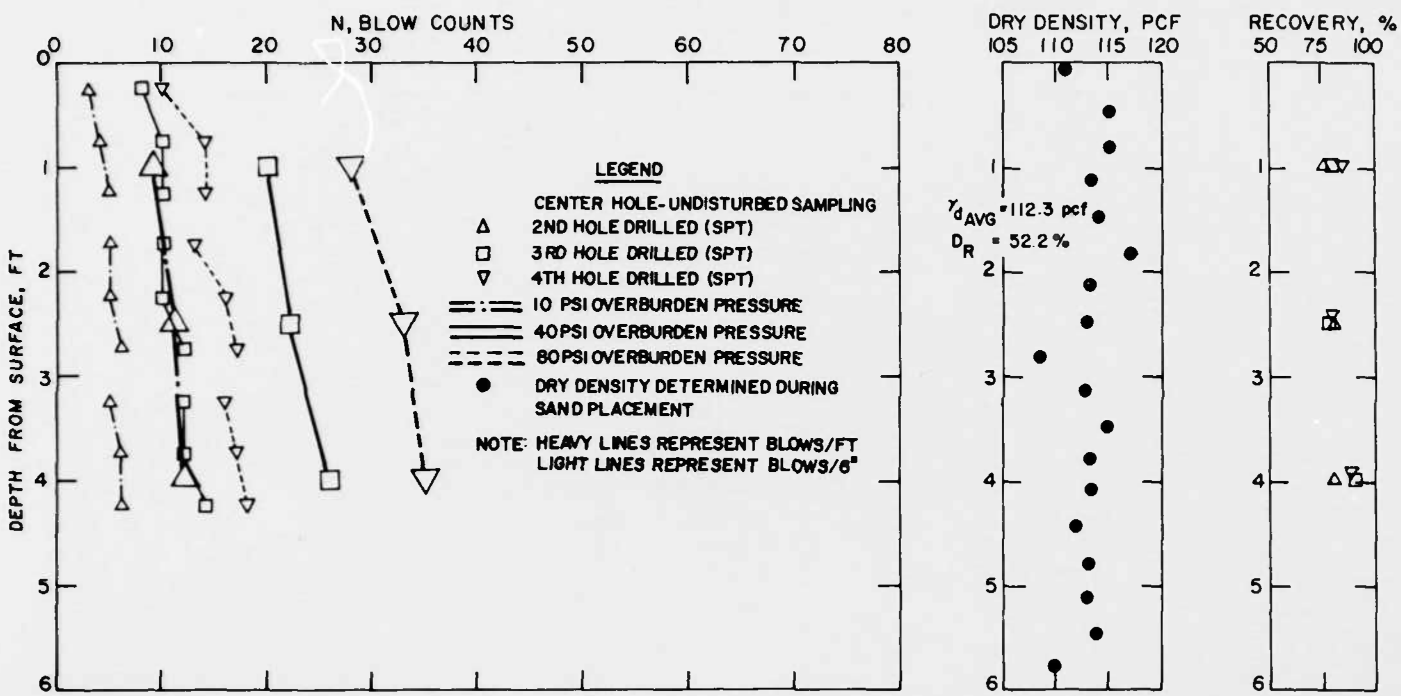
$$D_R = 0.85\left[\left|222(N) + 1600 - 53(\bar{\sigma}_v) - 50(C_u)^2\right|\right]^{1/2}$$

$r^2 = 0.90$, $\sigma = \pm 10.2\%$

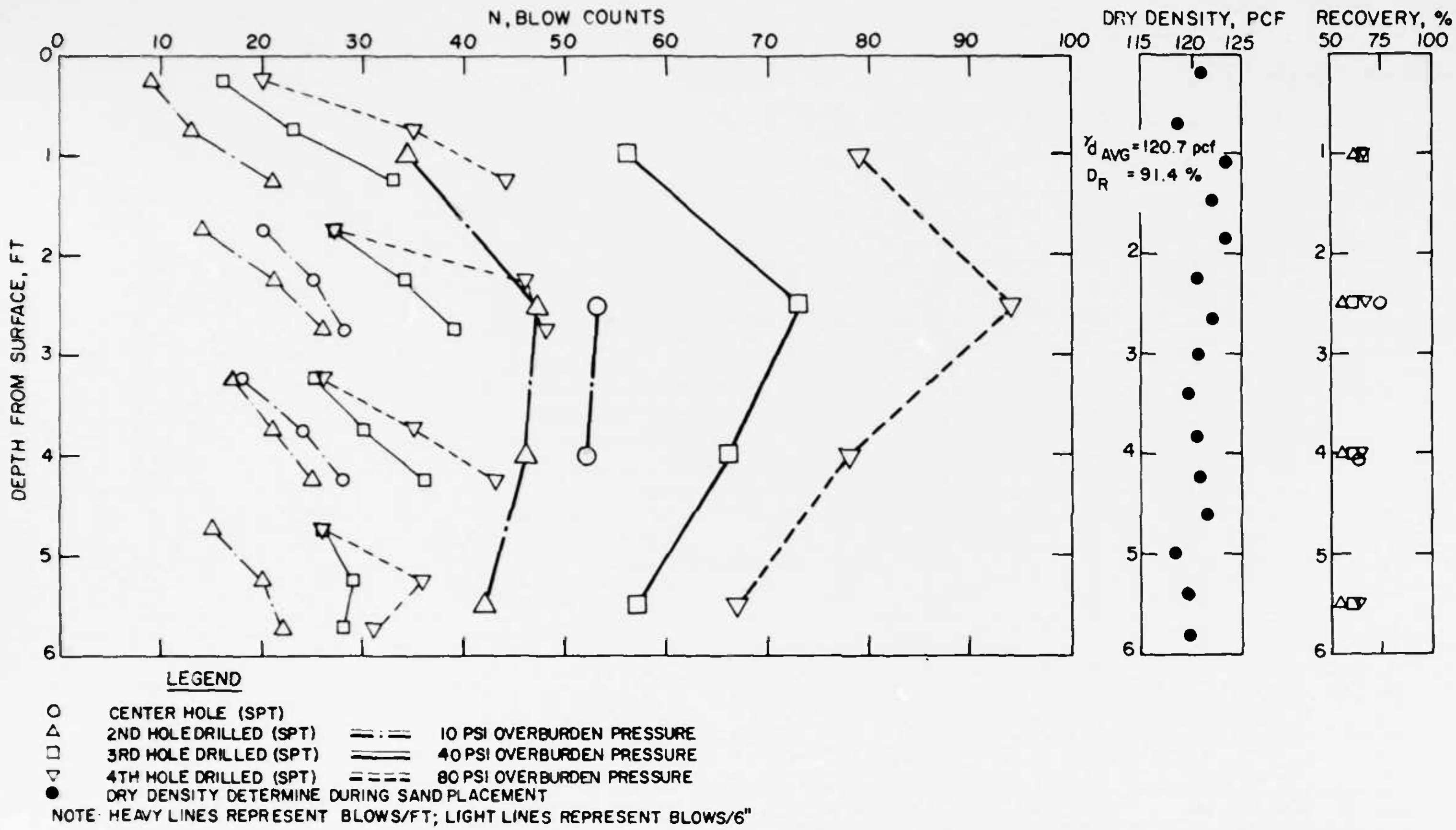
SET	EXPECTED	OBSERVED	DIFFERENCE
1	30.63634014	20.09999990	10.53634024
2	27.86693882	20.09999990	7.76693898
3	30.20452619	25.90000010	4.30452615
4	27.39143538	25.90000010	1.49143548
5	22.34214926	29.70000005	-7.35785073
6	25.71459603	29.70000005	-3.98540384
7	82.26362705	95.89999962	-13.63637209
8	82.26362705	95.89999962	-13.63637209
9	73.97496986	95.89999962	-21.92502904
10	83.24166966	95.89999962	-12.65832949
11	95.75510025	95.89999962	-0.14489919
12	106.93469524	95.89999962	11.03469574
13	102.64896870	95.89999962	6.74896974
14	108.77334404	95.89999962	12.87334478
15	45.52304316	49.30000019	-3.77695701
16	45.52304316	49.30000019	-3.77695701
17	51.90182686	50.50000000	1.40182686
18	56.38742161	50.50000000	5.88742191
19	59.80202961	51.69999981	8.10203004
20	62.45063925	51.69999981	10.75063980



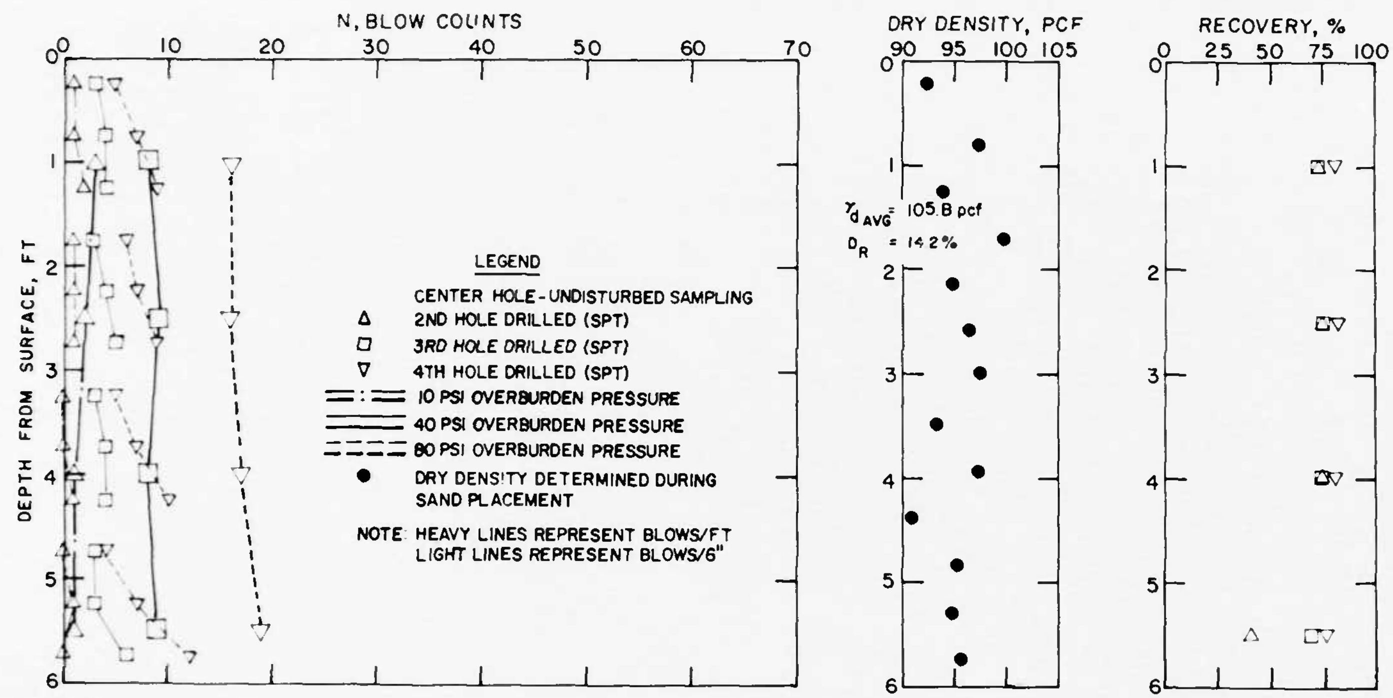
RESULTS OF STANDARD PENETRATION TEST
PLATTE RIVER SAND, SINGLE-HOSE RAINER
TEST 27, AUG 1975



RESULTS OF STANDARD PENETRATION TEST
PLATTE RIVER SAND, VIBRATED
TEST 28, AUG 1975

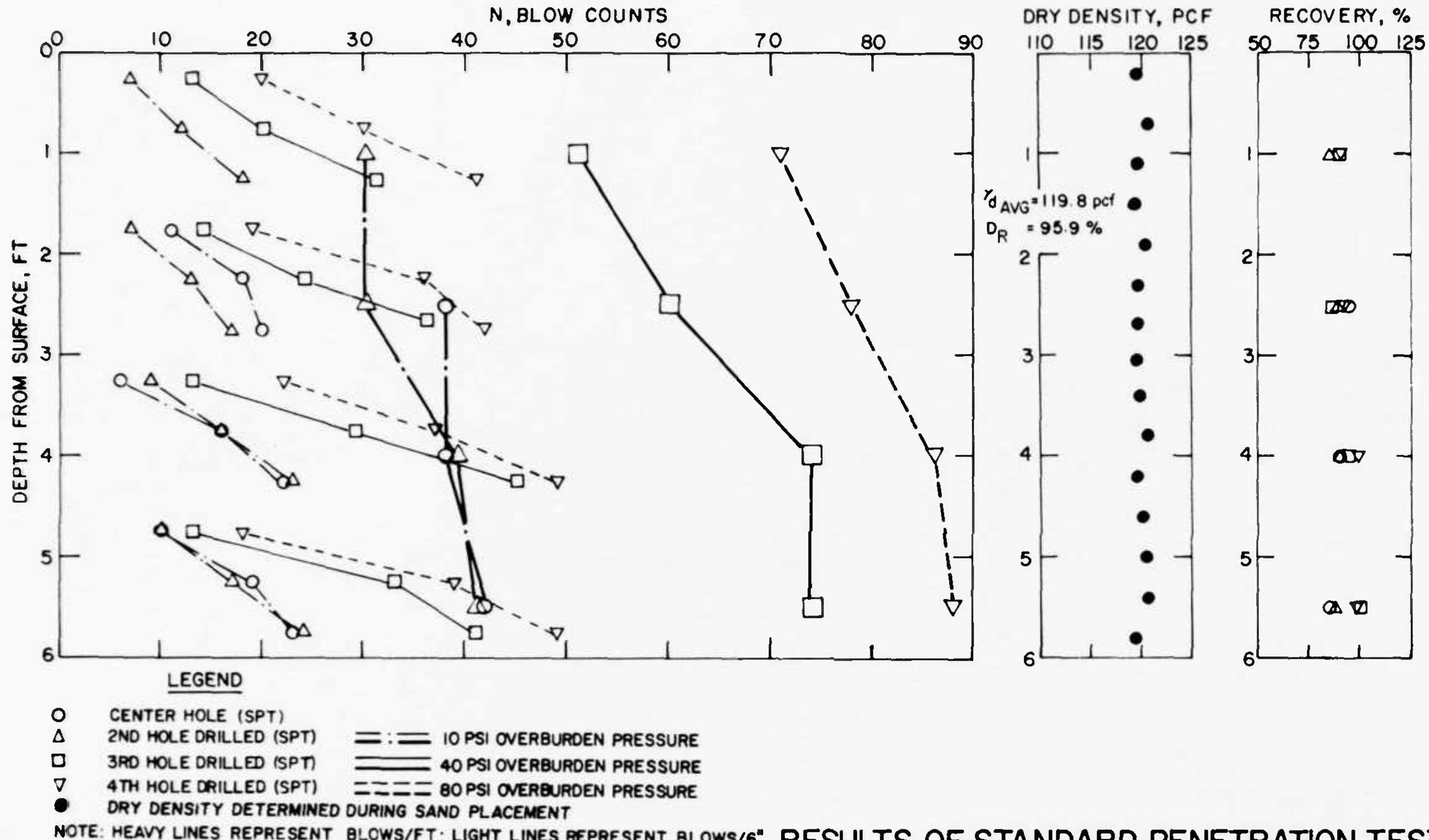


RESULTS OF STANDARD PENETRATION TEST
PLATTE RIVER SAND, VIBRATED
TEST 29, SEPT 1975

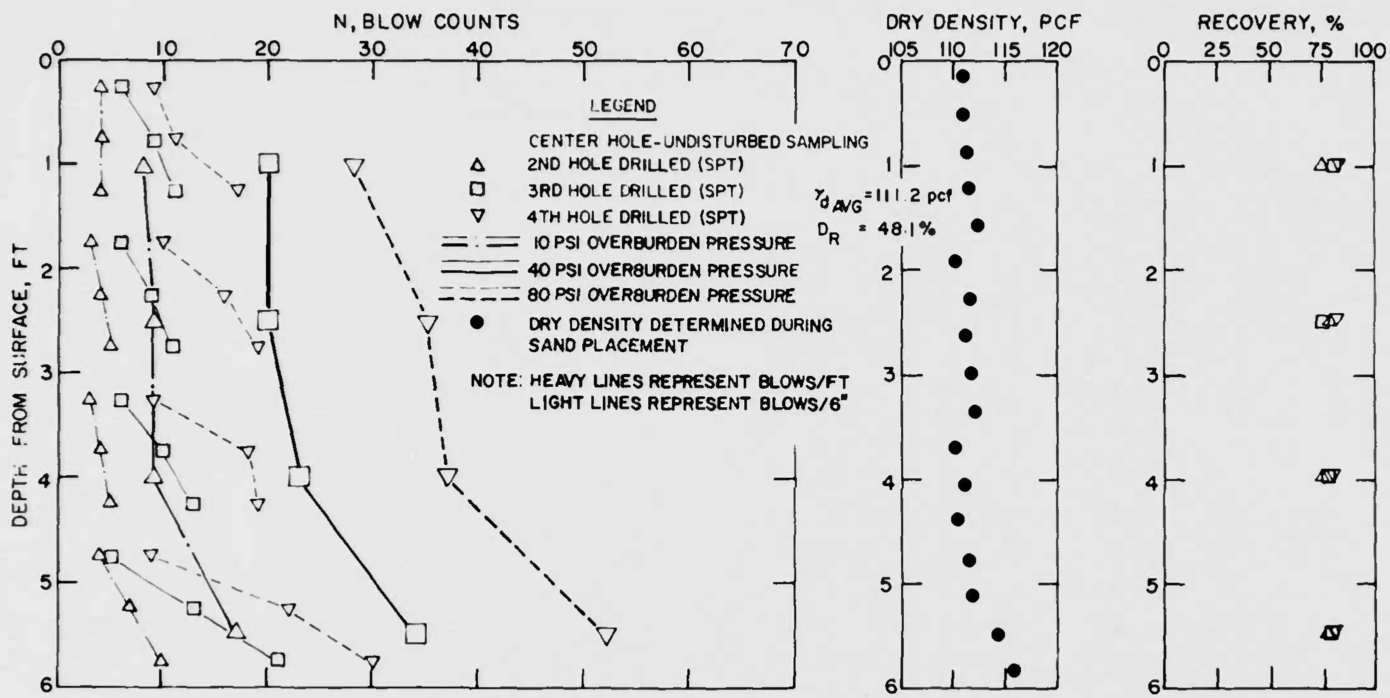


RESULTS OF STANDARD PENETRATION TEST
STANDARD CONCRETE SAND, SINGLE-HOSE RAINER
TEST 30, SEPT 1975

PLATE 4



RESULTS OF STANDARD PENETRATION TEST
STANDARD CONCRETE SAND, VIBRATED
TEST 31, OCT 1975



RESULTS OF STANDARD PENETRATION TEST
STANDARD CONCRETE SAND, VIBRATED
TEST 32, OCT 1975

PLATE 6

APPENDIX A: PETROGRAPHIC AND TEXTURAL ANALYSIS OF THE PLATTE RIVER AND STANDARD CONCRETE SANDS

DEPARTMENT OF THE ARMY
WATERWAYS EXPERIMENT STATION, CORPS OF ENGINEERS
P. O. BOX 631
VICKSBURG, MISSISSIPPI 39180

IN REPLY REFER TO WESSR

7 May 1976

MEMORANDUM FOR RECORD

SUBJECT: Petrographic and Textural Analysis of the Platte River and Standard Concrete Sands

General

1. This study consists of a petrographic and textural analysis and comparison of Platte River and Standard Concrete sands. The analysis included the determination of basic statistical parameters and degree of rounding, and the identification of the mineralogy.

Platte River Sand

2. Texture. The statistical parameters were calculated from the gradation curve plotted on probability paper. The results are:

a. Median grain size: -1.00ϕ* = 2.00mm

b. Mean grain size: -0.80ϕ = 1.74mm, very coarse sand**

c. Standard deviation: 1.51ϕ = 0.35mm, poorly sorted

d. Skewness: +0.23, fine skewed

e. Kurtosis: 0.91, mesokurtic

3. Mineralogy. Mineralogical analysis and quantitative identification were performed by petrographic microscope and binocular microscope. These data are given below:

a. Material coarser than the number 18 sieve (1.0mm or 0ϕ) was examined quantitative by binocular microscope. This material represents approximately 74 percent of total sample; mineral constituency is given below:

*mm = $2^{-\phi}$
**Wentworth scale

Mineralogy	Percent	Counting Error (Percent) for Counting 174 Grains
quartz	52	≠3.6
feldspar, undifferentiated	6	≠1.7
K-feldspar	17	≠2.8
rock fragments, chiefly granitic	24	≠3.3

b. Grain mounts were prepared for the number 35, 60, 120, and 200 sieves, and mineral identification was performed with the petrographic microscope. This data is given below:

(1) Passing the number 18 sieve (1.0mm or 0ϕ) and retained on the number 35 sieve (0.5mm or 1.0ϕ). This is approximately 15 percent of total sample.

Mineralogy	Percent	Counting Error (Percent) for Counting 110 Grains
quartz	53	≠5.0
K-feldspar	23	≠4.4
feldspar, undifferentiated	8	≠2.8
rock fragments, chiefly granitic	12	≠3.3
biotite	<1	na
opaques	<1	na
unknown	3	≠1.5

(2) Passing number 35 sieve (0.5mm or 1.0ϕ) and retained on number 60 sieve (0.25mm or 2.0ϕ). This represents 8 percent of total sample.

Mineralogy	Percent	Counting Error (Percent) for Counting 157 Grains
quartz	65	≠3.8
plagioclase	3	≠1.2
K-feldspar	26	≠3.5
biotite	3	≠1.2
other, opaques "heavies," and unknown	2	≠1.1

(3) Passing number 60 sieve (0.25mm or 2.0ϕ) and retained on number 120 sieve (0.125mm or 3.0ϕ). This is approximately 2 percent of total sample.

Mineralogy	Percent	Counting Error (Percent) for Counting 163 Grains
quartz	46	≠3.9
plagioclase	2	≠1.0
K-feldspar	34	≠3.6
biotite	4	≠1.6
opaques	7	≠2.2
"heavies"	4	≠1.6
unknown	2	≠1.0

(4) Passing number 120 sieve (0.25mm or 3.0ϕ) and retained on the number 200 sieve (0.074mm or 0.75ϕ). This is less than 1 percent of total sample.

Mineralogy	Percent	Counting Error (Percent) for Counting 144 Grains
quartz	29	≠3.6
plagioclase	20	≠3.3
K-feldspar	21	≠3.3
feldspar, undifferentiated	16	≠2.9
biotite	1	na
muscovite	<1	na
opaque	3	≠1.2
"heavies"	4	≠1.6
rock fragments	<1	na
unknown	6	≠1.8

c. Mineralogical Summary. The mineralogical composition of the total sample is presented in Table 1.

4. Particle Morphology. Figure 1 illustrates the general grain appearance of the number 18 (1a) and number 35 (1b) sieve splits. These views show that neither sphericity nor rounding is highly developed. The rounding is estimated to be "subrounded".

TABLE 1

Mineralogical Composition of Platte River Sand

Sieve No.	ϕ	mm	Fraction of Total Sample	Quartz	Plagioclase	K-feldspar	Feldspar Undifferentiated	Biotite	Muscovite	Opaques	Heavies	Rock Fragments	Unknown
18	0	1.000	0.74	38.5	-	12.6	4.4	-	-	-	-	17.8	-
35	+1.00	0.500	0.15	8.0	-	3.5	1.2	0.2	-	0.2	-	0.2	0.5
60	+2.00	0.250	0.08	5.3	0.2	2.1	-	0.2	-	0.2	-	-	-
120	+3.00	0.125	0.02	0.9	-	0.7	-	0.1	-	0.1	0.1	-	-
200	+3.75	0.074	0.01	0.3	0.2	0.2	0.2	-	-	-	-	-	0.1
200*	-	-	-	-	-	-	-	-	-	-	-	-	-
	TOTALS:		≈1.00	53.0	0.4	19.1	5.8	0.5	-	0.5	0.1	18.0	0.6

* Material passing number 200 sieve represents approximately one percent of sample and was not analyzed

a. Plus No. 18 sieve

b. Plus No. 35 sieve

Figure 1. Platte River sand

Standard Concrete Sand

5. Texture. The statistical parameters for this sand are given below:

a. Median grain size: $+1.00\phi = 0.5$mm

b. Mean grain size: $+0.40\phi = 0.76$mm, coarse sand

c. Standard deviation: $1.48\phi = 0.37$mm, poorly sorted

d. Skewness: -0.52, strongly coarse skewed

e. Kurtosis: 1.24, leptokurtic

6. Mineralogy. Mineralogical analyses were conducted by binocular and petrographic microscope and are given below for five size splits which represent approximately 98 percent of the sample.

a. Material coarser than the number 18 sieve (1.0mm or 0ϕ). This split comprises 27 percent of sample and was analyzed by binocular microscope.

Mineralogy	Percent	Counting Error (Percent) for Counting 361 Grains
quartz	66	≠2.5
feldspar, undifferentiated	1	≈≠0.7
rock fragments, chiefly chert	4	≈≠1.0

b. Material passing the number 18 sieve (1.0mm or 0ϕ) and retained on the number 35 sieve (0.5mm or $+1.0\phi$). This is 23 percent of total sample and analysis was by petrographic microscope.

Mineralogy	Percent	Counting Error (Percent) of Counting 191 Grains
quartz	88	≠2.2
plagioclase	<1	≈≠1.0
K-feldspar	4	≠1.3
feldspar, undifferentiated	4	≠1.3
rock fragments, chiefly chert	4	≠1.3

c. Material passing the number 35 sieve (0.5mm or +1.0ϕ) and retained on the number 60 sieve (0.25mm or +2.0ϕ). Analysis was by petrographic microscope. This represents 42 percent of total sample.

Mineralogy	Percent	Counting Error (percent) of Counting 200 Grains
quartz	90	≠2.2
plagioclase	≈0.5	<≠1.0
K-feldspar	6	≠1.7
rock fragments, chiefly chert	3	≠1.0

d. Material passing the number 60 sieve (0.25mm or +2.0ϕ) and retained on the number 120 sieve (0.125mm or +3.0ϕ). The analysis was by petrographic microscope and this split represents 4.5 percent of the total sample.

Mineralogy	Percent	Counting Error (Percent) for Counting 174 Grains
quartz	78	≠3.1
plagioclase	3	≠1.0
K-feldspar	4	≠1.5
feldspar, undifferentiated	6	≠1.7
opaques	2	≠0.9
rock fragments, (chert)	5	≠1.6
unknown	2	≠0.9

e. Material passing the number 120 sieve (0.125mm or +3.0ϕ) and retained on the number 200 sieve (0.074mm or +3.75ϕ). The analysis was by petrographic microscope and the split represents 1.5 percent of total sample.

Mineralogy	Percent	Counting Error (Percent) for Counting 171 Grains
quartz	66	≠3.5
plagioclase	7	≠1.8
K-feldspar	4	≠1.5
feldspar, undifferentiated	16	≠2.8

Mineralogy	Percent	Counting Error (Percent) for Counting 171 Grains
biotite	1	na
opaques	1	na
"heavies"	<1	na
rock fragments, (chert)	<1	na
unknown	4	≠1.5

f. Mineralogical Summary. The mineralogical composition of approximately 98 percent of the sample is given in Table 2.

7. Particle Morphology. Figure 2 illustrates two views of particles retained on the number 60 sieve. The grains are seen to be moderately spherical and may be approximately classed as subrounded to well rounded.

Comparison Between Platte River and Standard Concrete Sands

8. The principal comparitive parameters of the Platte River and Standard Concrete sands are shown in Table 3. The mineralogical, textural, and morphological comparisons are addressed below.

a. Mineralogy. The quartz, total feldspar, and rock fragment constituency of the two sand are considerably different, particularly with respect to quartz and feldspar. The differences in quartz and feldspar content may contribute indirectly to morphological or textural differences since the energy conditions which produce well developed sphericity and rounding also tend to destroy feldspar. Also, the presence of feldspar, which is vulnerable to chemical weathering, may lead to the development of fines, particularly clay minerals, in the sediment. The feldspars in these two sands are not excessively weathered although the Platte River contained 5.8 percent undifferentiated feldspar venus 1.7 percent for the Standard Concrete sand. This results in approximately 23 and 29 percent of the total feldspars in the respective samples being weathered such that they were not identifiable. The rock fragments in the Platte River sands are granitic and consist of gravel and sand size aggregates or fragments of quartz and K-feldspar.

Chert and subordinate amounts of other sedimentary rock fragments occur in the Standard Concrete sand. These chert fragments are susceptible to weathering and appear so. Whereas the granitic rock fragments are restricted to the coarser sand and gravel fractions of the Platte River, the chert in the Standard Concrete sand is somewhat more evenly distributed.

TABLE 2

Mineralogical Composition of Standard Concrete Sand

Sieve No.	ϕ	mm	Fraction of Total Sample	Quartz	Plagioclase	K-feldspar	Feldspar Undifferentiated	Biotite	Muscovite	Opaques	Heavies	Rock Fragments	Unknown
18	0	1.000	0.270	17.8	-	-	0.3	-	-	-	-	8.9	-
35	+1.00	0.500	0.230	20.0	0.2	0.9	0.9	-	-	-	-	0.9	-
60	+2.00	0.250	0.420	37.8	0.2	2.5	-	-	-	-	-	1.3	-
120	+3.00	0.125	0.045	3.5	0.1	0.2	0.3	-	-	0.1	-	0.2	0.1
200	+3.75	0.074	0.015	1.0	0.1	0.1	0.2	tr	-	-	-	tr	0.1
200*	-	-	0.020	-	-	-	-	-	-	-	-	-	-
	TOTALS:		1.000	80.3	0.6	3.7	1.7	-	-	0.1	-	11.3	0.2

* Material passing number 200 sieve represents approximately one percent of sample and was not analyzed

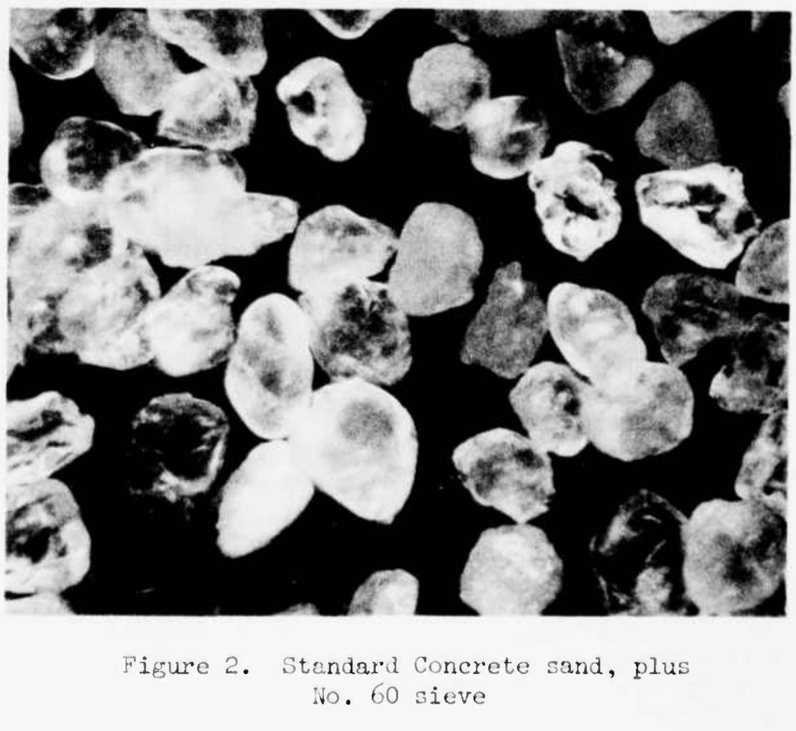


Figure 2. Standard Concrete sand, plus No. 60 sieve

TABLE 3

Principal Comparative Parameters of Platte River and Standard Concrete Sands

	Mineralogy (Percent)				Texture					Morphology	
Sand	Quartz	Feldspar	Rock Fragments	Other	Md (ϕ)	Mz (ϕ)	σ (ϕ)	Sk	K	Sphericity	Rounding
Platte River Sand	53.0	25.3	(igneous) 18.0	3.7	-1.0	-0.8	1.51	+0.23	0.91	Less	Less
Standard Concrete Sand	80.3	6.0	(chert) 11.3	2.4	+1.0	+0.4	1.48	-0.52	1.24	More	More

b. Texture. The Platte River sand is considerably coarser than the Standard Concrete sand. However, their respective sortings, as defined by standard deviations, are quite similar and they are both poorly sorted. Bimodality, a characteristic of gravels and coarse sands, is exhibited to a certain degree by both sands and is shown on the histogram of Figure 3. The calculated values of skewness show that the Platte River sand contains an excess of fine particles (fine skewed), whereas the Standard Concrete sand has an excess of coarse particles (coarse skewed); this is also apparent from the histograms (Figure 3). The Kurtosis values indicate that the relative sorting in the tails versus the center of the distribution is nearer to a normal distribution in the Platte River sand. The Standard Concrete sand, however, exhibits considerably more material in the tails of the corve than does a normal distribution. Although both sediments are classed as sands in the Unified soil classification system (which classifies material under 5mm as sands) the Platte River material would be classified as a gravel in the Wentworth system since the latter classification limits sands to material finer than 2mm.

c. Particle Morphology. Qualitatively it is the writer's opinion that the Platte River sand is distinctly less rounded and exhibits less sphericity than the Standard Concrete sand. This conclusion is based upon observations while counting 748 Platte River and 1098 Standard Concrete grains and is more or less evident from Figures 1 and 2. The higher degree of rounding and sphericity of the Standard Concrete Sand is due to the sedimentary source of this sand is indicated by the presence of chert rock fragments which were derived from chert-bearing limestones. Thus, many of the quartz grains have been derived from the weathering of sandstones and are, therefore, second order (or higher) and have been subjected to more than one episode of transportation. On the other hand, the Platte River sand has an igneous source, indicated by the abundant K-feldspar and granitic rock fragments. The quartz grains in this sand are first cycle and have been less extensively rounded during transportation.

DAVID M. PATRICK
Research Geologist
Engineering Geology and
Rock Mechanics Division

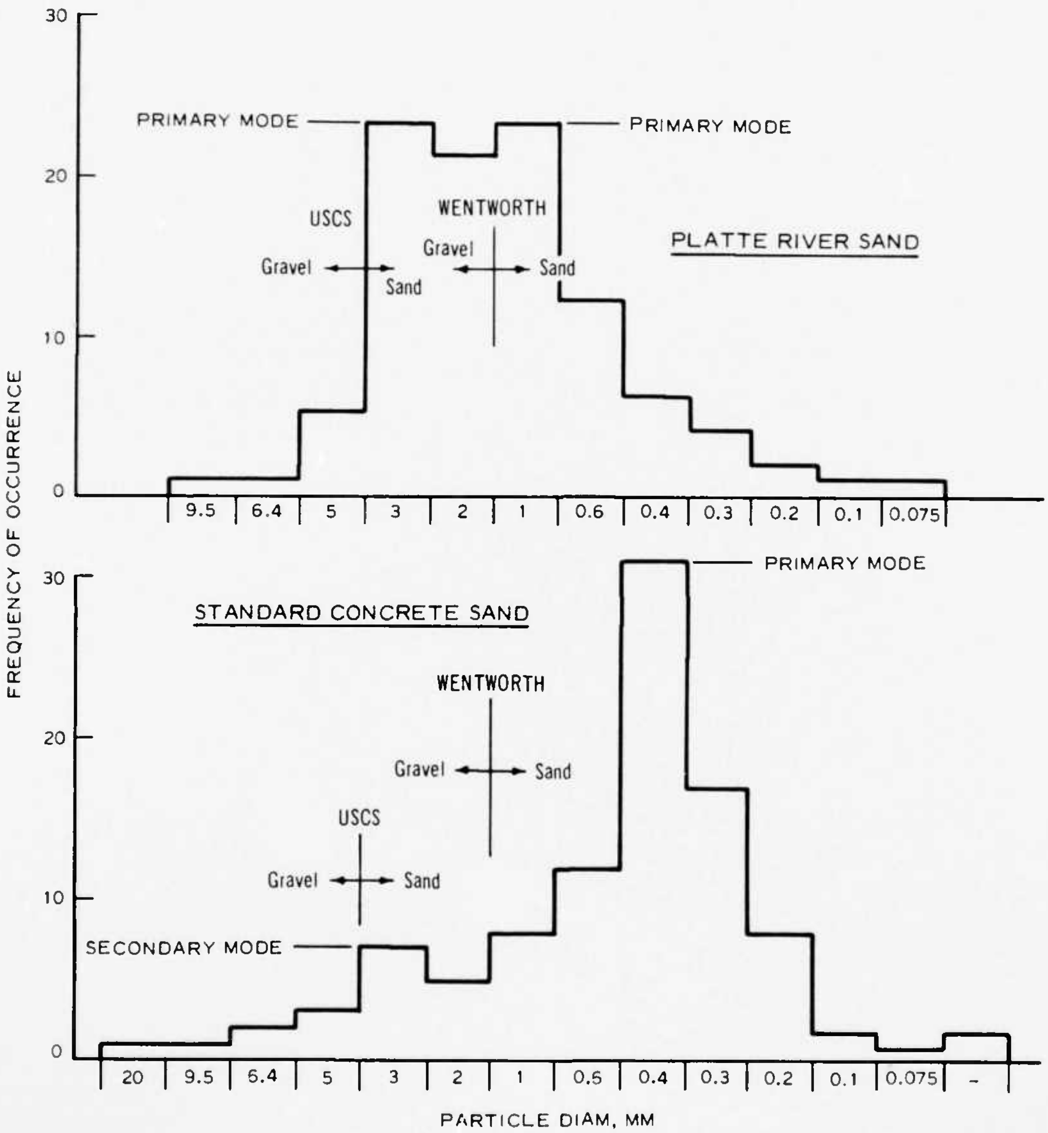


Figure 3. Histograms of Plat‵‶ River and standard concrete sands
NOTE: V = Primary and seconday modes

APPENDIX B: RESULTS OF BUREAU OF RECLAMATION CHECK TESTS ON PLATTE RIVER SAND DENSITY

United States Department of the Interior
BUREAU OF RECLAMATION
ENGINEERING AND RESEARCH CENTER
P.O. BOX 25007
BUILDING 67, DENVER FEDERAL CENTER
DENVER, COLORADO 80225

IN REPLY
REFER TO: 1541
330.

DEC 1 6 1976

Mr. Wayne A. Bieganousky
Geodynamics Branch
Department of the Army
Waterways Experiment Station
Corps of Engineers
Post Office Box 631
Vicksburg, MS 29180

Dear Mr. Bieganousky:

The minimum density tests on Platte River sand requested by letter of October 12 to Mr. John Merriman are completed. The results show an average minimum density of the sand to be 102.9 lb/ft^3. This is about 10 lb/ft^3 greater than the minimum density of the sand we used in our penetration resistance research study, but compares to the values you are obtaining in your research on the Standard Penetration Test.

We have just received copies of Report 1 on "Liquefaction Potential of Dams and Foundations" (October 1976) and shall be interested in this and future work on the Standard Penetration Test. Let us know if we can help you further on this.

Sincerely yours,

Howard J. Cohan

Howard J. Cohan, Chief
Division of General Research

In duplicate

Enclosures

AMERICAN REVOLUTION BICENTENNIAL 1776-1976

DATA WORK SHEET

South Platte River Sand

58H-1

Minimum Density Test (Volume Mold = 0.100 ft^3)

Scoop Method

Mold + Soil =	19.15	19.13	
Mold =	8.89	8.89	
Soil =	10.26 lb	10.24 lb	Avg = 10.25 lb

$$\gamma_d = 10.25 \text{ lb} \div 0.100 \text{ ft}^3$$
$$= 102.5 \text{ pcf}$$

Pour Spout Method

Dia. Spout = 1-1/2 in.

(1/2-in. Spout - Soil Bridged)

Mold + Soil =	19.23	19.21	
Mold =	8.89	8.89	
Soil =	10.34 lb	10.34 lb	Avg = 10.33 lb

$$\gamma_d = 10.33 \text{ lb} \div 0.100 \text{ ft}^3$$
$$= 103.3 \text{ pcf}$$

Sand Cone Device for 0.1 ft^3

Soil bridged in valve opening (7/16 in.)

9 Dec 1976
LJC

In accordance with ER 70-2-3, paragraph 6c(1)(b), dated 15 February 1973, a facsimile catalog card in Library of Congress format is reproduced below.

Bieganousky, Wayne A

Liquefaction potential of dams and foundations; Report 2: Laboratory standard penetration tests on Platte River sand and standard concrete sand, by Wayne A. Bieganousky and William F. Marcuson III. Vicksburg, U. S. Army Engineer Waterways Experiment Station, 1977.

1 v. (various pagings) illus. 27 cm. (U. S. Waterways Experiment Station. Research report S-76-2, Report 2)

Prepared for Office, Chief of Engineers, U. S. Army, Washington, D. C., under CWIS 31145.

Includes bibliography.

1. Dams. 2. Foundations. 3. Liquefaction (Soils). 4. Relative density. 5. Sands. 6. Soil tests. 7. Standard penetration tests. I. Marcuson, William Frederick, joint author. II. U. S. Army. Corps of Engineers. (Series: U. S. Waterways Experiment Station, Vicksburg, Miss. Research report S-76-2, Report 2)

TA7.W34r no.S-76-2 Report 2

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